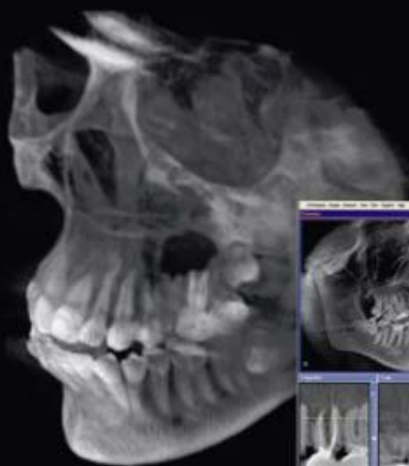


Joachim E. Zöller
Jörg Neugebauer

Cone-beam Volumetric Imaging in Dental, Oral and Maxillofacial Medicine

Fundamentals, Diagnostics and Treatment Planning



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Cone-beam Volumetric Imaging **in Dental, Oral and Maxillofacial Medicine**

Fundamentals, Diagnostics and Treatment Planning

With contributions by:

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Foreword

The diagnostic requirements in dental medicine are determined not only by oro-maxillofacial surgical therapeutic concepts but also by the increasing esthetic expectations of the patient. The trend to performing even extensive dental surgical procedures on an outpatient basis requires minimally invasive surgical techniques so that any necessity for postoperative inpatient treatment is largely avoided. Successfully performing minimally invasive surgical techniques requires a comprehensive three-dimensional diagnostic system, which also reduces the risk of complications. Therefore, we at the University of Cologne quickly initiated the use of three-dimensional imaging for computer-assisted surgery.

However, three-dimensional radiological imaging has not yet been routinely established in dental medicine and generally dentists have used the orthopantograph for diagnostic purposes. The development of cone-beam volumetric imaging was intended to allow the use of legally permitted levels of dental radiation for a wider range of applications. Using this technique a computed tomographic scan of the cranium is an acceptable item for billing under medical fees schedules in Germany. In addition to the use of the technique for clear dental indications, it was also important to assess how good it would be in detecting asymptomatic conditions. In the initial trial phase, we were surprised by the frequency of discovery of asymptomatic pathological entities by chance. This led to the idea of illustrating the various, sometimes rare, findings in an atlas to provide the user of cone-beam volumetric imaging with a reference for use in day-to-day assessments.

The GALILEOS software primarily used in this atlas is unique because it produces a three-dimensional orthopantograph that can be studied three-dimensionally using the assessment window. Naturally, this dynamic assessment cannot be illustrated in a book. Therefore, we have compiled a DVD with an original data set and numerous on-screen videos of assessments in different dental disciplines in order to demonstrate the identification of anatomical and pathological structures.

We hope that the first-time reader will find much enjoyment in this introduction and we hope to provide the experienced reader with a reference work for the various findings.

Prof. Dr. Dr. J. E. Zöller
Dr. J. Neugebauer
and co-authors

The dentist's working volume is hardly more than one liter, but this human body part contains within a very confined space a multitude of bones, vessels, nerves and anatomical structures of singular importance to the patient's quality of life and communication options.

Therefore, radiological diagnostics has represented an essential source of information for the dentist's spatial orientation since the beginnings of modern dental medicine. However, classical radiological techniques still depict this information in two dimensions. Three-dimensional radiological diagnostics enables the dentist to acquire accurate spatial information. However, regular utilization of this technology has been limited by the high equipment cost and the radiation exposure, which is not justifiable in all indications. Therefore, these systems have essentially developed under radiological considerations and do not meet the dentist's needs for pathological assessment.

The GALILEOS system that has been scientifically tried and proven at the University of Cologne is the first method that enables the dentist to perform three-dimensional diagnostics in dental radiology. All indications in which cone-beam volumetric imaging is indicated in the oro-maxillofacial area are excellently described in this atlas. The numerous, well-documented case examples provide the new user with an orientation, particularly with regard to the recognition of secondary findings, since the entire facial cranium is always documented in a single image.

However, in addition to diagnostics, the use of this three-dimensional information is equally important for the course of further treatment. The oral surgery, orthodontic and implantological therapy options are presented with numerous examples. The rare indications for computer-assisted navigation or orthognathic surgery also illustrate the options available in system applications.

In this work, the team of authors with Prof. Zöller discuss the scientific studies carried out in recent years and demonstrate the utilization of the technique, both scientifically and in practice, using numerous patient examples. Modification of three-dimensional image data for dental radiology thus adds a new therapeutic dimension for the dentist. To meet the increasing demands of our patients for minimally invasive procedures and optimal restoration of lost or damaged dental substance, three-dimensional diagnostics with familiar dental imaging is another important tool for high-quality dentistry.

Prof. Dr. Fouad Khoury

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Technology

1 Fundamentals of Cone-beam Volumetric Imaging Technology

Erwin Keeve, Jochen Kusch, Joachim Hey and Lutz Ritter

Few new technological developments have revolutionized medical diagnostics as extensively as has x-ray technology. Even before *Wilhelm Conrad Röntgen* officially announced his discovery on December 28, 1895, it was used among others by the Austrian physician *Guido Holzkecht*.

With the development of x-ray computered tomography (CT) in the 1960s and its first use for clinical studies in 1972 by *Godfrey Hounsfield*, radiological tomography attained widespread use and today is one of the essential imaging techniques in medical radiology. It is a technically mature and clinically widely accepted method and complements classical x-ray panoramic radiography in many areas.

The development of spiral CT in 1989 and the introduction of multislice detector systems in 1998 further accelerated CT techniques and led to the ability to acquire volume data.

A subsequent development of CT technology, digital volume tomography (or cone-beam volumetric imaging (CBVI) as we will refer to it in this book) has been established in recent years. The technology is frequently used in maxillofacial radiology because of its characteristic low radiation dose, high spatial resolution and lower cost compared with CT. Its technology and possible applications are discussed in this chapter.

1.1 Computed Tomography

Image reconstruction in modern computed-assisted imaging techniques such as magnetic resonance imaging (MRI), single-photon emission CT (SPECT) and positron emission tomography (PET) is based on mathematical algorithms that permit axial tomographic imaging of the human body without superimpositioning. The progressive development of detector technology and reconstruction mathematics and the reduction of radiation exposure have allowed the generation of increasing numbers of single-slice images, particularly in CT.

In contrast to the classical process of radiology, where a single slice is sharply imaged but all other layers in the beam path overlay the desired image, the digital imaging process of CT permits the use of computer-supported reconstruction algorithms to generate image slices of the human body without superimpositions.

This is always based on the superimposition-free measurement of the distribution of a tissue layer in a transverse slice. Integrals are measured over this distribution along curves. The separation of the individual slices is performed by the measurement process itself: that is, focus and detector are always in the plane of the slice to be examined, and the electromagnetic beam scans only this slice. Consequently, image reconstruction in the CT process is a two-dimensional (2D) issue (special processes such as x-ray panoramic radiography, for example, are not considered in this chapter).

However, with a strictly predefined positioning of focus and detector, the measured intensity distribution of the x-ray beam passing through the object only provides information on the sum of all attenuations that the electromagnetic beam has undergone in the object. Each object point must therefore contribute to many independent measurements to permit the computation of a radiation attenuation value for this specific 2D point using image reconstruction.

The principles of image reconstruction can be explained using the simplest design of a parallel-beam device (fan beam and detector ring devices require complicated algorithms, but these can be derived from the algorithms used in parallel-beam devices by means of coordinate transformation). A linear scanning movement is required in this very simple type of scanning. The intensity measured at the detector thus depends only on the projection angle and the momentary position of the measuring system during linear scanning, and obviously on the intensity of the unattenuated radiation. The path of the momentary scanning beam through the object is used as the integration path.

In this fashion, the starting point of the linear 2D reconstruction problem is attained. The distribution of the attenuation capacity in the slice examined – and accordingly the radiation attenuation value for precisely one 2D object point – is computed from the totality of the measured intensities. The oldest image reconstruction processes are algebraic processes and offer the simplest explanation of CT image reconstruction.

Imagine that the object to be scanned is made up of small square cells (pixels). Further, the linear scanning movements are carried out in a finite number of equidistant intervals with a finite number of strictly predefined projection directions. Figure 1-1 illustrates this situation for the very small number of four pixels and each of two scan positions for two different projection directions.

In this simple model, the individual measurements from a measurement beam passing through the object are the sum of the values of all pixels detected by the beam. In this example, a linear equation system determines the four attenuation values sought and two projection directions are sufficient for accurately computing the equation system. If the grid to be reconstructed is finer, only an iterative solution of the extensive equation system is possible. This particular reconstruction process, primarily discussed to provide a basic understanding of reconstruction processes, is, therefore, no longer used in CT. Understanding modern analytical reconstruction algorithms requires a sound understanding of Fourier transformations and folding integrals, a discussion of

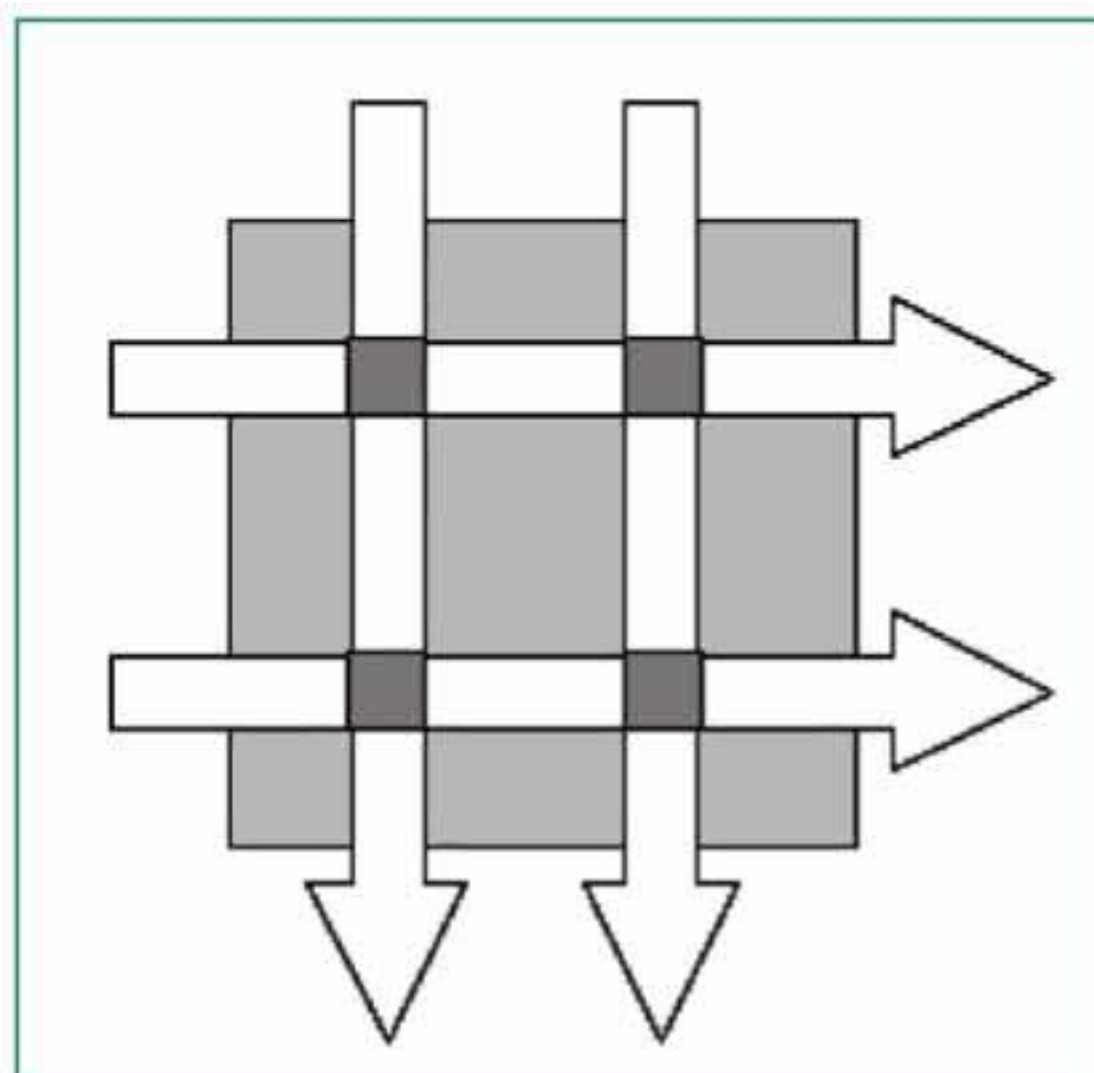


Fig 1-1 Principle of algebraic image reconstruction.

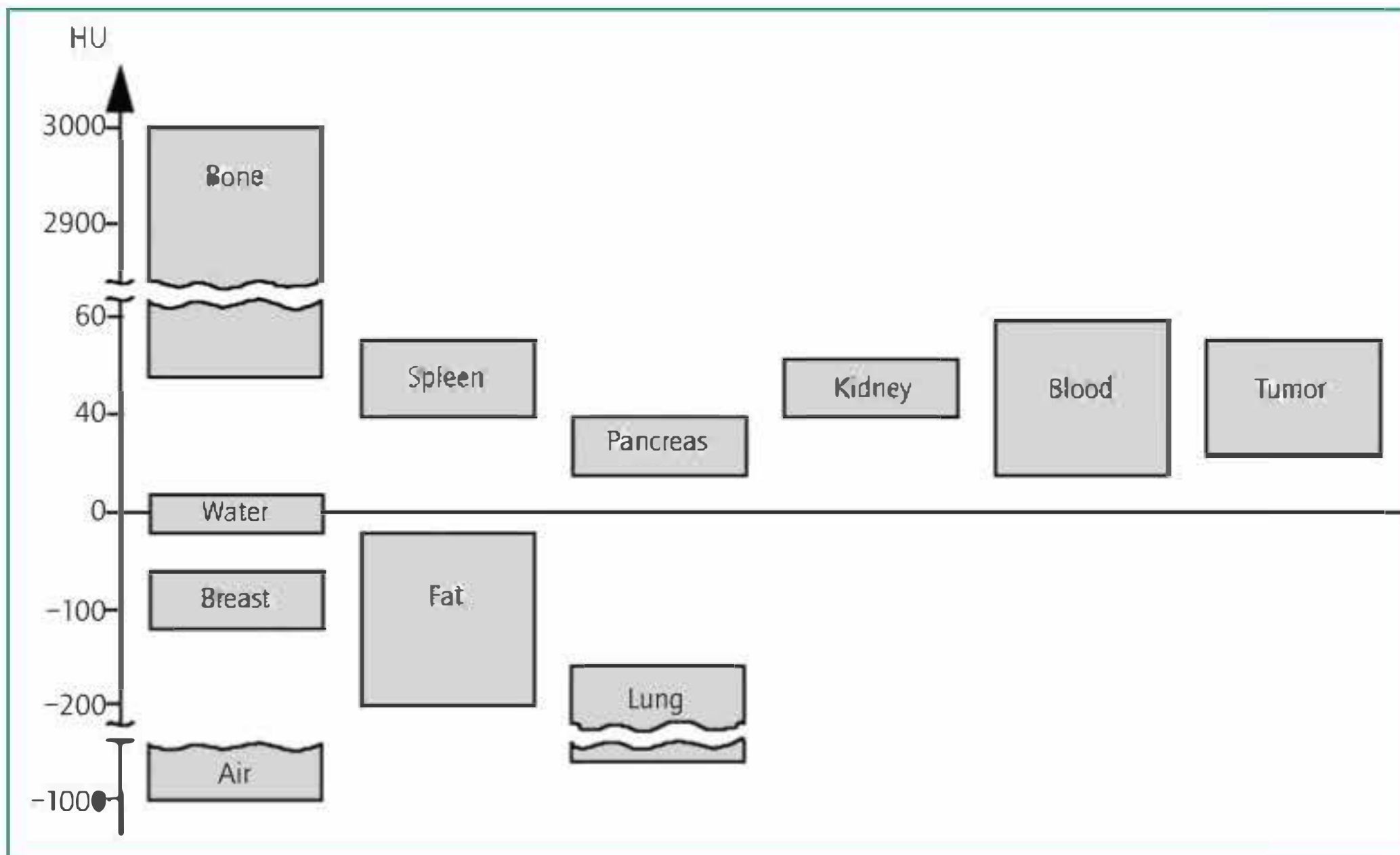


Fig 1-2 Hounsfield units: Godfrey N. Hounsfield (1919–2004) received the Nobel Prize in Medicine in 1979.

which is beyond the scope of this book. A comprehensive description of the various algorithms for image reconstruction can be found in standard textbooks or in “Bildgebende Systeme für die medizinische Diagnostik” [“Imaging Systems for Medical Diagnostics”] edited by *Heinz Morneburg*.¹

Every pixel of the computed slice image represents a radiation attenuation value m , which is given in so-called Hounsfield units (HU). An HU value of 0 is equivalent to the radiation attenuation value of water, while an HU value of -1000 corresponds to the value of air. The radiation attenuation values of various body substances and tissues are given in Figure 1-2. It clearly shows that some substances have similar values for their attenuation ranges and consequently cannot be differentiated using CT imaging. In contrast, bone is the only body substance with a very high radiation attenuation value (greater than 300 HU) and accordingly is easy to identify using a threshold value operation.

The Hounsfield scale starts at -1000 HU and generally ends at around 3000 HU, although it is theoretically open ended at the high end of its range. From this numerical range, only the integers are used to convey image information and these are assigned to values on a gray scale. Consequently, 12 bits are required for each pixel of a tomograph to resolve some 4000 possible gray levels. However, the majority of CT scanners use 16 bits (2 bytes) per pixel, and the tomographs are stored in the file format devised by the American College of Radiology and the National Electrical Manufacturers Association.² This file format is a standard that enables medical images and information to be exchanged when derived from devices and systems made by different manufacturers. Along with the actual tomographs, various patient and image information such as the patient's name and date of birth, equipment type, slice number, slice spacing and pixel size can be stored and archived on the respective medium.

Since neither a display unit nor the human eye can resolve the approximately 4000 possible gray levels of a pixel in a CT image, a so-called windowing operation is carried out after data collection. This means that a user-defined segment of the 4000 gray levels is displayed on the full grayscale of a display unit, such as on the 256 grayscale levels of a video monitor. All CT values that are

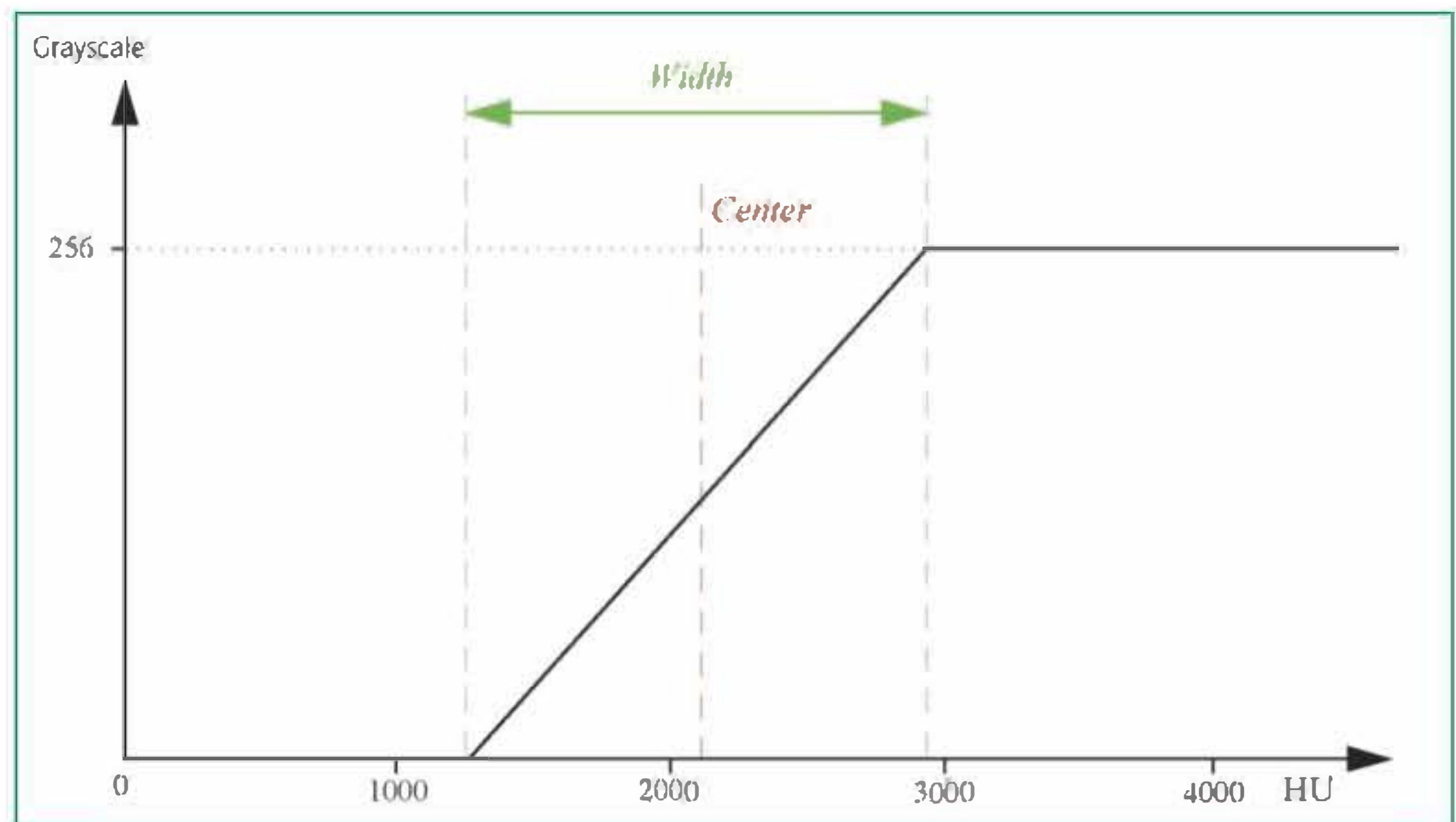


Fig 1-3 The windowing principle: 256 instead of 4000 gray levels.

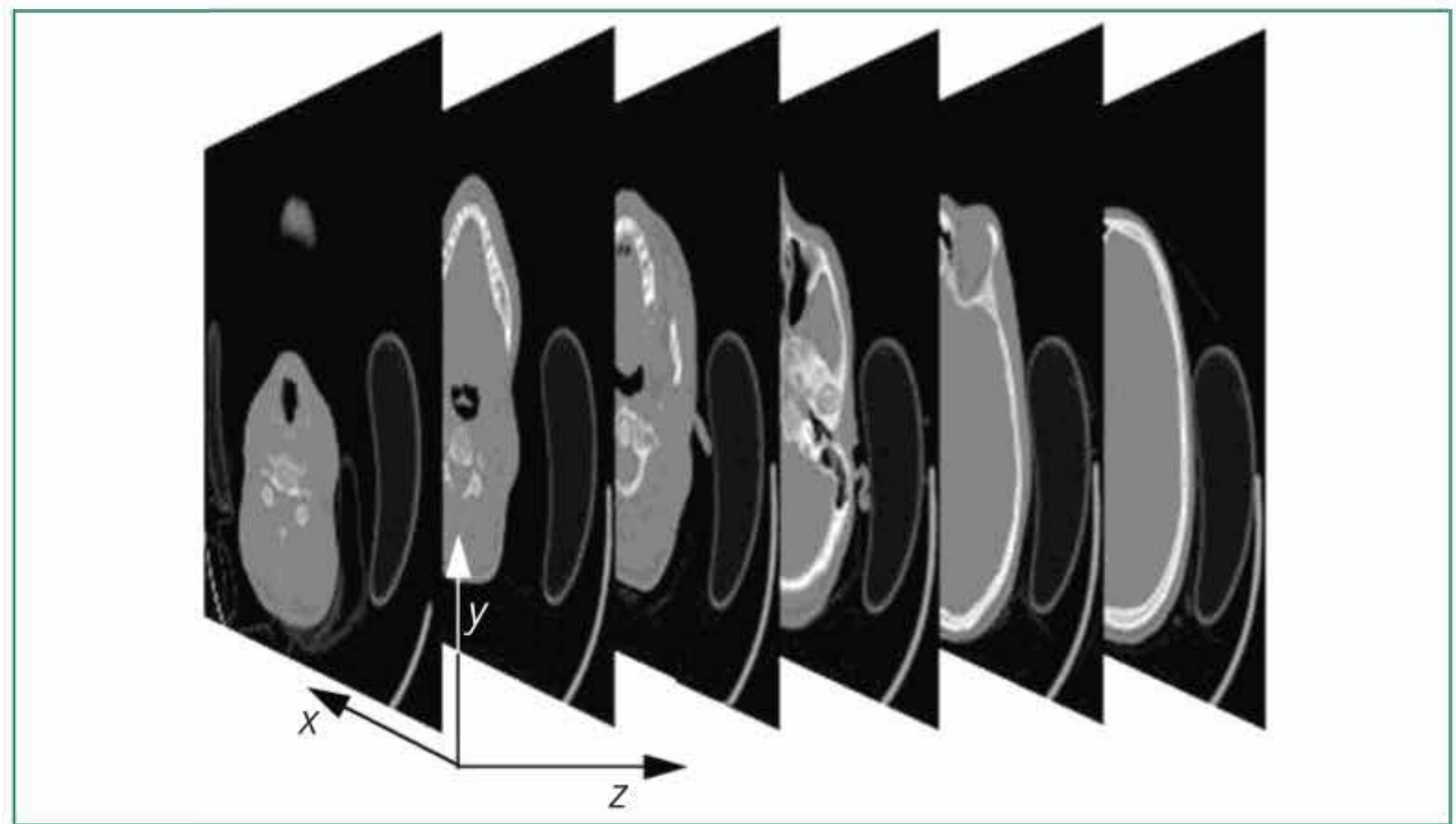


Fig 1-4 Computed tomography.

higher than the upper window value are displayed in white; all CT values that are less than the lower threshold are displayed in black. The principle of this type of windowing is shown in Figure 1-3. Using the two parameters *center* and *width*, different radiation attenuation value ranges can be selected and specific body substances can be visualized. CT images prepared in this way are shown in Figure 1-4.

1.2 Cone-beam Volumetric Imaging

Up to this point, we have discussed CT processes that enable superimposition-free measurement of the radiation attenuation values in a single transverse tissue slice. More modern reconstruction methods, such as those used in spiral CT, are also based on 2D image reconstruction algorithms. Here, volume images are created via secondary reconstructions from stacks of slices. This section will discuss the genuine three-dimensional (3D) reconstruction methods of cone-beam volumetric imaging (CBVI).

The move from parallel-beam to a real beam tomography has two fundamental advantages: a higher rate of acquisition because no stop is required for parallel shift of the detector system during rotation of the scanning system around the patient, and a better utilization of the tube power, since the beam collimation of a thin needle beam is an enormous waste of the x-ray radiation generated.

Considering this approach further, it makes sense to utilize not only one collimated fan but the entire cone-beam from the radiation source (Figure 1-5). The cone-beam enables the transition from imaging one or several individual slices to imaging a defined anatomical region. An exact definition of what constitutes a fan-beam system versus a cone-beam system has not been established, because in modern multiple-slice systems, the external fans are no longer strictly parallel. Therefore, the decisive factor is not image geometry but the 3D image reconstruction methods used, which differ substantially from the classical reconstruction methods used in 2D tomographs.

Different approaches to cone-beam reconstruction and different implementations are available. The basic problem associated with cone-beam reconstruction is that details of an object to be imaged are displayed on different detector elements, depending on their respective distance from the central axis (the axis of rotation) of the imaging system (Figure 1-6). The data that are gathered by a single detector element in a complete rotation no longer represent a planar slice. The greater the cone angle, the greater the contribution of structural details of other slices to the signal and the greater the resulting potential inconsistencies, which makes 3D image reconstruction of cone-beam data disproportionately more complicated than its 2D counterpart.

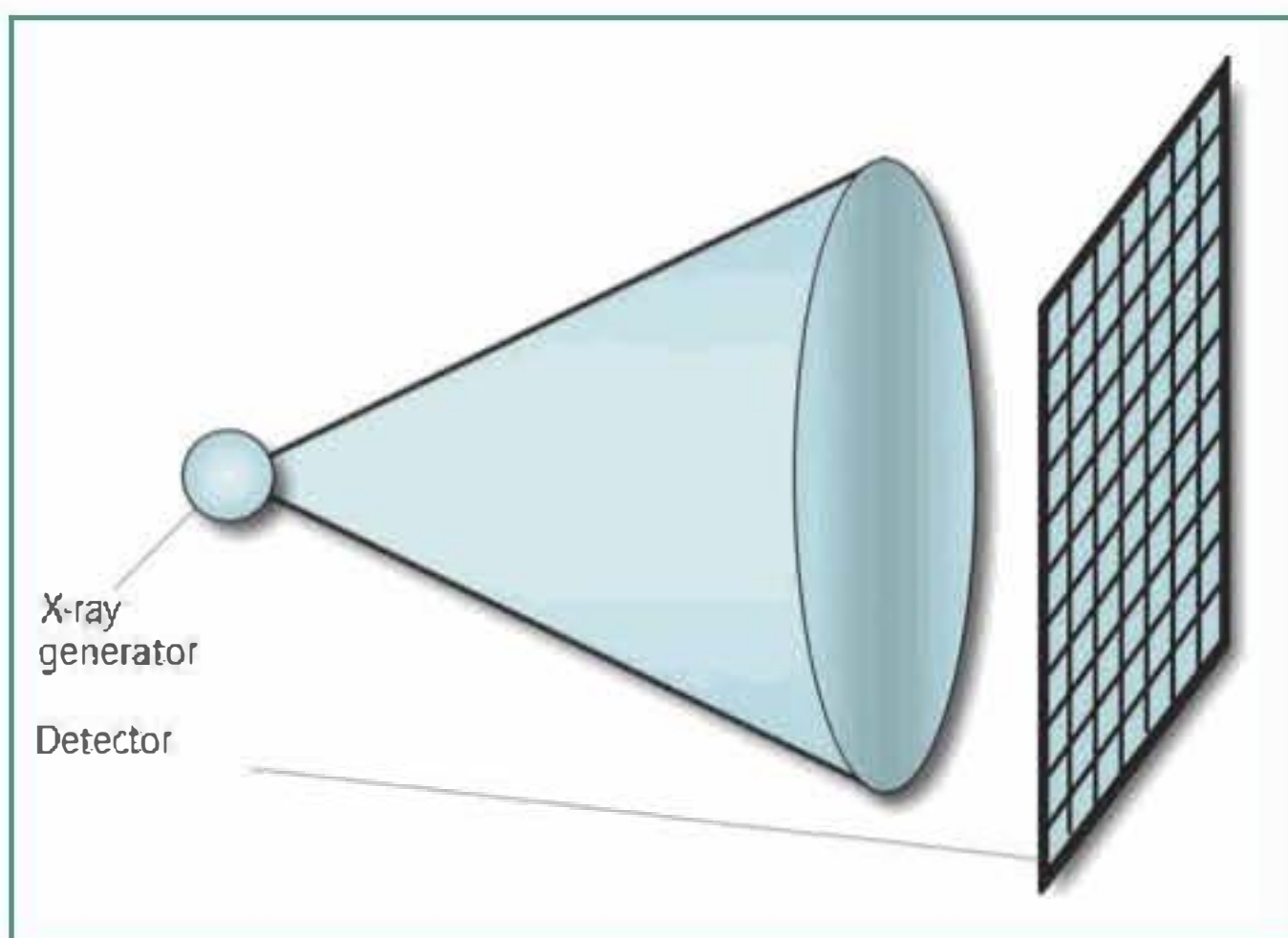


Fig 1-5 Cone-beam geometry.

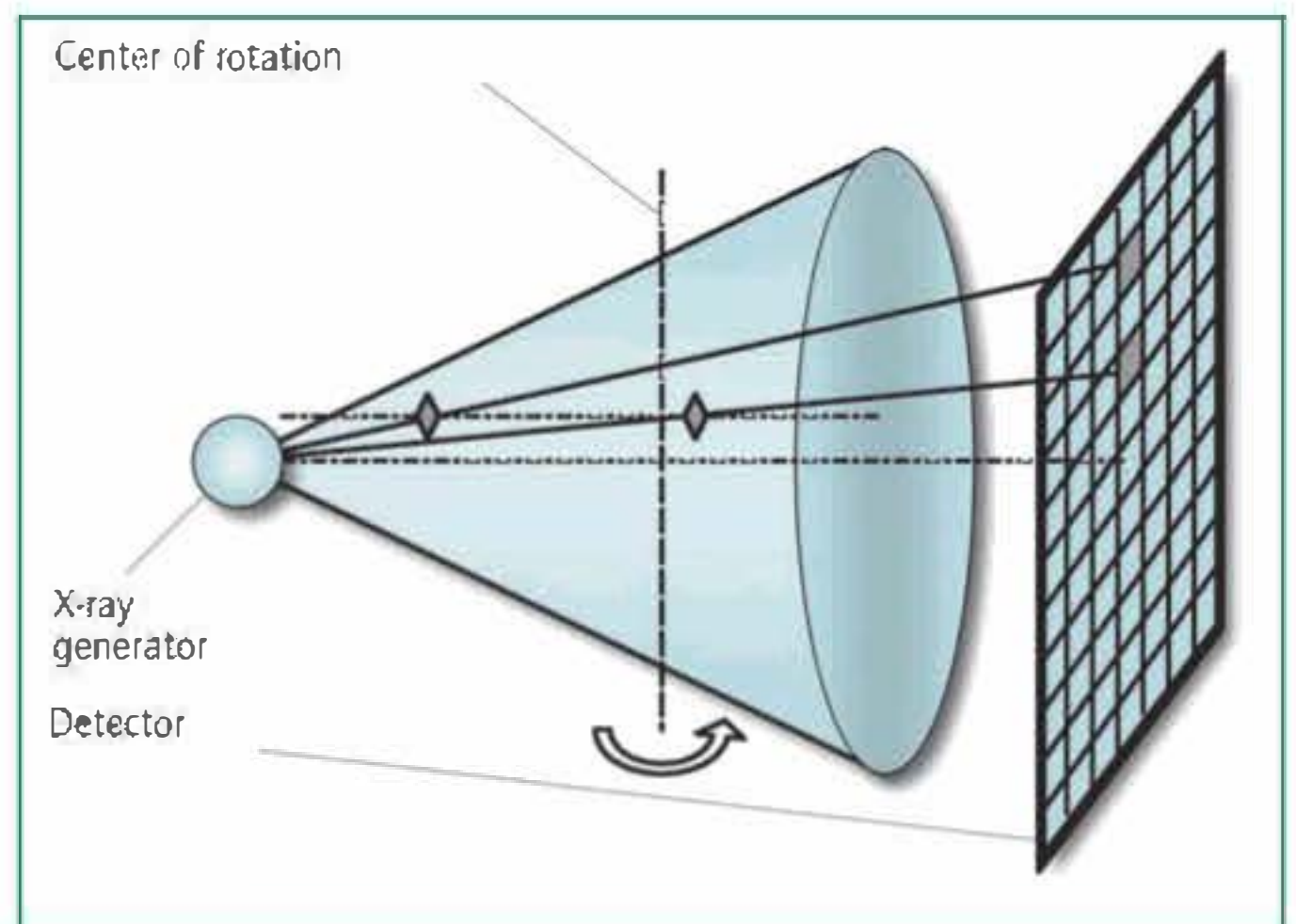


Fig 1-6 Fundamental problems in cone-beam reconstruction.

Fortunately, this does not mean that image reconstruction from cone-beam data is impossible. Probably the most frequently used cone-beam reconstruction algorithm is the Feldkamp algorithm developed in 1984 by L.A. Feldkamp, L.C. Davis and J.W. Kress. This so-called FDK cone-beam reconstruction is an approximation of the exact reconstruction approach that was developed originally for technical examinations and used planar detectors. The starting point of the FDK cone-beam reconstruction is the idea of independently processing each fan-shaped area in the cone-beam, defined by one detector line and the radiation source, as if it were a 2D fan-beam projection. The 3D image reconstruction is thus reduced to many 2D image reconstructions. To maintain the focus of this book, we refer to the book by T. Buzug³ for a further discussion.

Although the required image reconstruction algorithms were already available in 1984, cone-beam systems were still not ready for medical application for some time, because appropriate detector systems were unavailable. One significant problem was that the tremendous quantities of data generated had to be transferred very rapidly from the rotating scanning system to the external devices for further processing. However, devices have recently been developed that are capable of using the cone-beam geometry for 3D image reconstruction, both for conventional C-arm systems and for CT. CT devices are called multiple-array systems or volume CTs; C-arm devices are referred to as isocentric systems, because the radiation source and the image receiver move around a fixed center of rotation. Figure 1-7 illustrates such a C-arm system.



Fig 1-7 The isocentric C-arm Arcadis Orbic 3D (Siemens).

1.3 Use of Cone-beam Volumetric Imaging in the Operating Room

Since the mid-1990s, work has been proceeding on a mobile 3D imaging system for use in the operating room. Such a system – possibly coupled to a navigation system – would be helpful in shortening procedures and preventing complications, particularly in complicated fractures in joints and the spinal cord, but also for complex surgical procedures on the visceral cranium.

The first approaches to using mobile CT units in the operating room were not successful because of the limited access allowed by the table pillar and the anesthesia area. This problem was solved by the integration of CBVI into mobile C-arms.

Because C-arms are used in most operating rooms for x-ray examination, no additional equipment is required. However, the C-arm must be configured isocentrically (i.e., the radiation source and the image receptor must move around the pivot of the C-arm) to permit 3D imaging of the torso. The Siemens Arcadis Orbic 3D (Figure 1-7) achieves isocentricity mechanically, while the Ziehm Vario 3D achieves it by adjustment by a motor during imaging. Both devices can also be used as conventional C-arms. An illustration of the image data taken with the Arcadis Orbic 3D system is shown in Figure 1-8.

The systems permit integration of the most current BrainLAB, Medtronic, Praxim and Stryker navigation systems (Figure 1-9). The interoperative use of a 3D C-arm combined with a navigation system eliminates the onerous and fault-prone recording of the preoperative image data while the patient is lying on the operating table. Here, too, both systems offer the opportunity to use both 2D and 3D imaging for navigation.

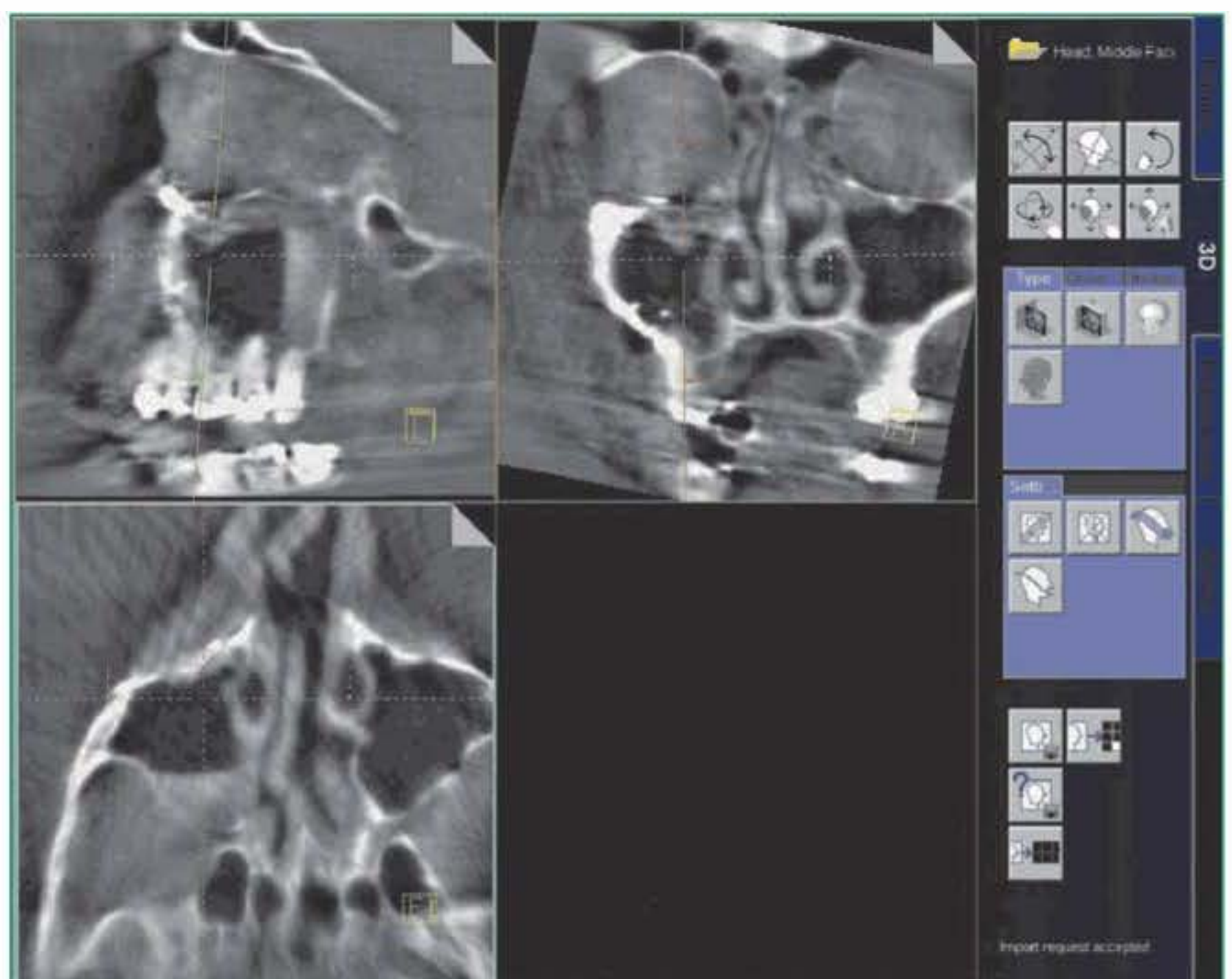


Fig 1-8 Imaging with the Siemens Arcadis Orbic 3D, an isocentric C-arm device for fracture treatment after impact trauma. (With kind permission of the Clinic and Outpatient Clinics for Oral and Maxillofacial Surgery of the Hamburg-Eppendorf University Clinics.)



Fig 1-9 Left: BrainLAB optical navigation instrument. Right: prototype of a Navigation-to-Go system from the MEM research laboratory.

Consequently, digital volume tomography with mobile C-arms has resulted in mobile 3D x-ray systems that require less space, less effort and provide better patient access than conventional intraoperative CT systems, simplifying clinical workflow and, in addition, being substantially more economic.

1.4 Use of Cone-beam Volumetric Imaging in Dentistry

The new CBVI technology faces the challenges of dental practice and clinics. A 3D imaging system should be integrated into the dental practice. Here, integration means incorporation into the existing spatial structure of the practice and into the workflow of the dentist, as well as presenting a continuous service concept from preparing and starting the imaging process to the actual assessment, and providing support in the planning of the subsequent process, if possible.

In a conventional dental practice, there are generally no separate rooms for diagnostics, as would be commonplace in radiology. Therefore, the equipment must be integrated into the local situation and into existing x-ray rooms, just as is currently the case for conventional panoramic systems. This influences the dimensions and radiation exposure acceptable if additional construction needs are to be avoided.

It is a great advantage for the procedures in the practice if the CBVI device is not more complicated to operate than conventional panoramic systems. The preparation for taking a 3D image should not interfere with practice operations. To this end, a simple patient positioning system is important.

In the new CBVI technology, a volume is usually generated around the isocenter, the actual rotational center of the system (Figure 1-10). If this volume is small, additional means are required to accurately locate the target volume and to position the patient with reference to the isocenter and target volume. The same applies to systems that allow free positioning of the patient within the rotational range of the system. In systems that permit a large target volume, pre-positioning is less critical.

In the CBVI systems, the total volume is computed from many individual images taken during rotation – as are all other views, such as panoramic presentations and transverse slices (Figure 1-11).

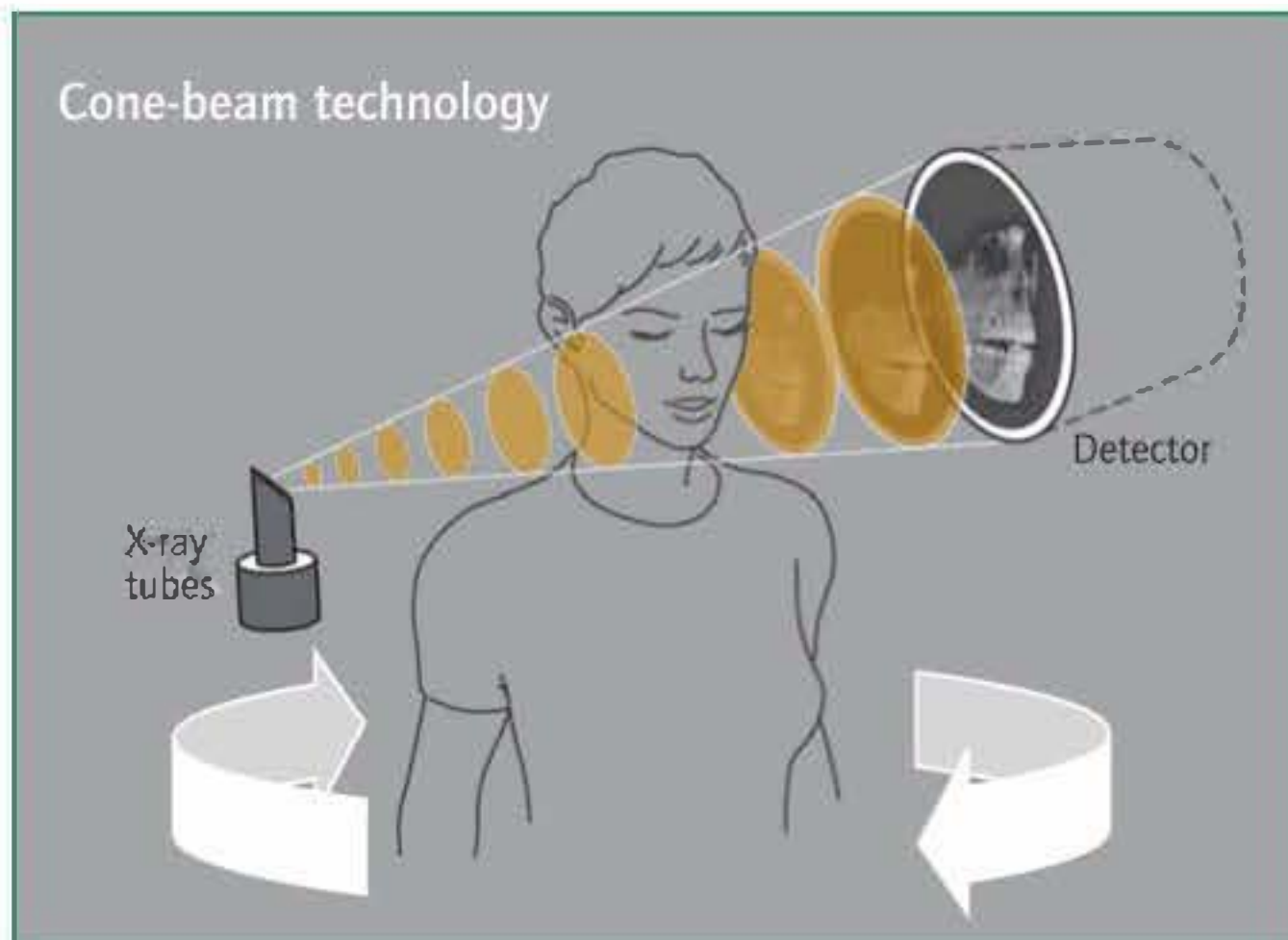


Fig 1-10 Cone-beam geometry of a dental CBVI system.



Fig 1-11 Radiographic range of a dental CBVI system.

Clinical indication	Imaging method	Effective dose (μSv)
Primary diagnosis of impacted teeth	Panoramic	5–45 (digital) ^{4,5}
		16–54 (film) ^{5,6}
	Occlusal Film	7 (digital) ⁷
Diagnosis of complex wisdom teeth	Panoramic	5–45
	Frontal cephalic	1.6–3.4 (digital) ⁸
Implant planning	Panoramic	5–45
	Transversal slices	3–12 ⁹
	3D computed tomography	150–1270 ^{6,10}
	3D cone-beam volumetric imaging	29–330 ^{4,10}

Table 1-1 Overview of the different radiation dosages in dental x-ray diagnostic procedures.

There are no false images with CBVI, such as those that can occur with conventional panoramic systems, where an incorrect setting of the parameters for the panoramic curve or the position of the transverse slice acquisition (TSA) may require the scan to be repeated. The entire set of views in CBVI can be corrected afterwards, if necessary.

However, as in conventional panoramic systems, the patient must be immobilized during the actual imaging (scan), so that image quality is not compromised. In conventional panoramic systems, any movement of the patient appears as a misalignment of the image beginning at a particular point, with the image sharpness before and after the movement remaining unaffected. In the CBVI systems, artifacts may occur, and image quality suffers overall. Therefore, short imaging times and an immobilization that is comfortable for the patient are required. Modern systems enable scanning times of less than 15 seconds. In general, it is advantageous both for dental office

operations and for the patient's comfort and hence cooperation if the patient can be easily positioned in the imaging system, in a seated or standing position if possible.

An important aspect for the acceptance of the new 3D technology in dentistry is patient exposure to radiation. Modern CBVI systems permit 3D images to be acquired for equivalent radiation exposure to that received in a conventional panoramic film or a conventional image set such as panorama with TSA or a periapical status from film. An overview of applied radiation doses is given in Table 1-1. The CBVI system has significantly lower radiation exposure levels than CT, even lower than the dedicated cranial CT systems. The exposure level from one scan is less than the annual environmental radiation exposure by a factor of 50 to 100 (effective dose depending on the system is between 15 and 100 μ Sv).

The main challenge is achieving maximum image quality at the lowest possible radiation exposure. However, as described below, these requirements are opposing, so compromises must be made. Depending on indication and patient size, the dose rate of the system can be adjusted to ensure diagnosability at the least exposure. A further dose reduction is achieved via an optimally adjusted x-ray generation system, permitting sharper images using pulsed radiation and a small focus (focal spot). Again, there are two opposing issues: the smaller the focus, the lower the tube output can be configured. This can prolong scan times, which, in turn, can have negative implications on image quality.

To obtain the maximum contrast for bone, teeth and soft tissue, it is advantageous if the radiation range is in the low-energy range (60–90 kV); higher voltages (120 kV) are used in standard CT, for example. The optimization of a CBVI system for use in dental imaging is thus indication driven and must be worked out in detailed studies.

CBVI systems generate volume image data that are geometrically accurate – they are in the correct anatomical relationship, so that undistorted measurements can be made – in contrast to conventional 2D projection images. The 2D views (slices or projections) computed from CBVI data usually have a similar resolution as the CT slices in the horizontal plane. In the vertical plane, however, CBVI data sets frequently achieve higher resolutions than CT but contrast is usually higher in CT. Compared with conventional panoramic images, the reconstructed panoramic images have a different appearance but provide essentially the same diagnostic information. Moreover, they lack the inevitable artifacts associated with conventional panoramic views, such as superimposition of the spine. The challenge is making the additional information provided by this new 3D technology accessible to the user at an acceptable price.

A fundamental aspect of 3D imaging is good software and a consistent software concept. As in other fields, software is becoming increasingly important in dentistry. In the world of 3D imaging, enormous amounts of data are available that can only be accessed by the user through intuitive software. To enable the physician to understand such large amounts of image data effectively, computer-aided summation of image information has to be available. Various levels of information can be offered. The first level provides an overview of the acquired scan. This can be achieved either by recalculated 2D projections of the data volume (e.g. panoramic) or by 3D rendering (e.g. 3D volume rendering). In either overview, the user is able to pick up and localize pathological findings. Therefore, the algorithms used have to be adapted to the possible pathological changes in the image and allow these to be visualized. For further evaluation, the user can then enter the second, more detailed, level of information (e.g. slice views). Here one is able to assess exactly the extension of the process and its relation to the neighboring structures. This approach is followed not only in dentistry when utilizing CBVI, but also in standard CT, where visualization software can provide maximum intensity projections or segmented 3D renderings.

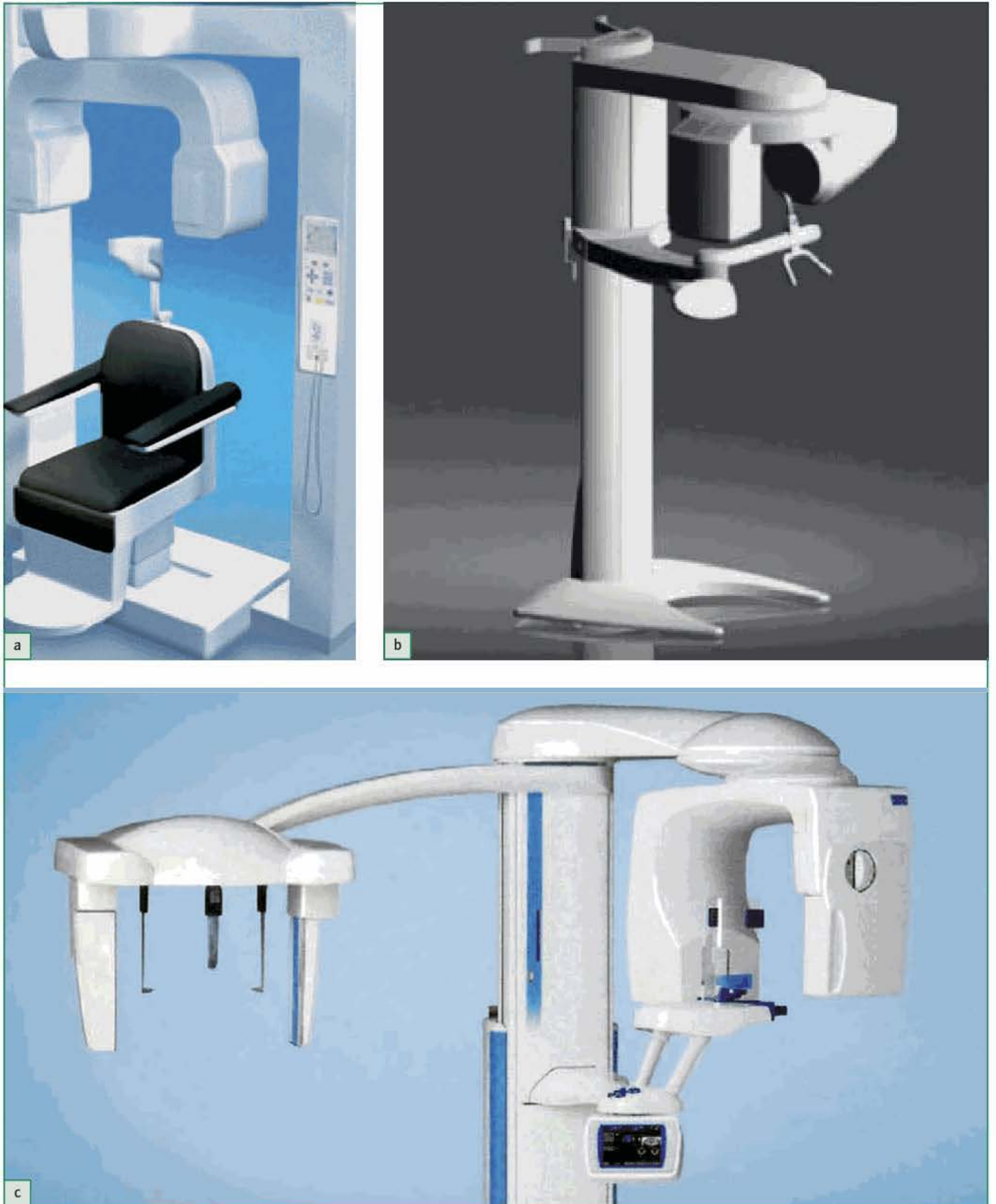


Fig 1-12 Cone-beam volumetric imaging systems in development or shortly before market entry. (a) Accuitomo from Morita; (b) GALILEOS from Sirona; (c) Promax 3D from Planmeca.

Currently, various manufacturers offer CBVI systems (see Figure 2-3). The NewTom system by the Italian company QR (see Figure 2-2) was constructed for supine patients and generates a large volume measuring 10 to 20 cm in edge length in a 36-second scan. Hitachi's MercuRay system is available in three different variations with different fields of view and is designed for a seated patient. Here, the time required for imaging is 10 seconds. The American company Imaging Sciences offers its i-CAT system (Figure 2-3a), which performs a scan in 10–40 seconds, depending on the resolution, with a field of 17 cm in diameter and a depth of 13 cm.

Figure 1-12 shows the Accuitomo system of the Japanese company Morita, the Promax 3D system recently announced by the Finnish company Planmeca and the GALILEOS system of the German company Sirona. The Accuitomo is intended for a seated patient and generates a small field of view (diameter 4 cm, depth 3 cm); Promax 3D covers a field of view with an 8 cm edge length in a scan time of 18 seconds, and the GALILEOS system is suitable for both the seated and the supine patient with a scan time of 14 seconds and a field of view of 15 cm edge length.

1.5 The Imaging Sequence in Cone-beam Volumetric Imaging

The imaging sequence of a modern CBVI system consists of the following four basic components, as do all classical x-ray systems used in medical diagnostics:

- the x-ray tube, generating the x-ray radiation
- the generator, supplying the x-ray tube with energy
- the detector, converting the x-ray radiation to an image signal after it passes through the patient
- the device, linking the tube, patient and detector with each other.

A diagram of the imaging geometry and the essential components of a CBVI system is shown in Figure 1-13.

The characteristics of the x-ray radiation generated by an x-ray tube can be easily adapted to the requirements of the respective examination. The radiation quality (also called the radiation hardness) is determined by the level of the applied voltage, and the intensity depends on the level of the selected current. Both quantities can be independently adjusted within the permissible output parameters of the tube.

One parameter characterizing the image quality (modulation–transfer function (MTF), see below) is the size of the focal spot. The electrodes in the tube are accelerated to nearly the speed of light by the voltage applied between the cathode and the anode; they then hit a tungsten target incorporated into the anode and are slowed down 30% to 65%. This deceleration generates x-ray radiation. The required anode currents for imaging operations are between a few hundred milliamperes and 2 A. Most dental CBVI systems use anode currents of approximately 5 to 25 mA. To obtain a sharply defined focus on the anode, the electrons must be focused using suitable auxiliary electrodes. In the simplest case, this can be a single suitably shaped electrode (Wehnelt electrode) at cathode potential. To optimize the emitted radiation cone for the respective system (detector and geometry), a first collimation is achieved by a lead tube in the housing itself.

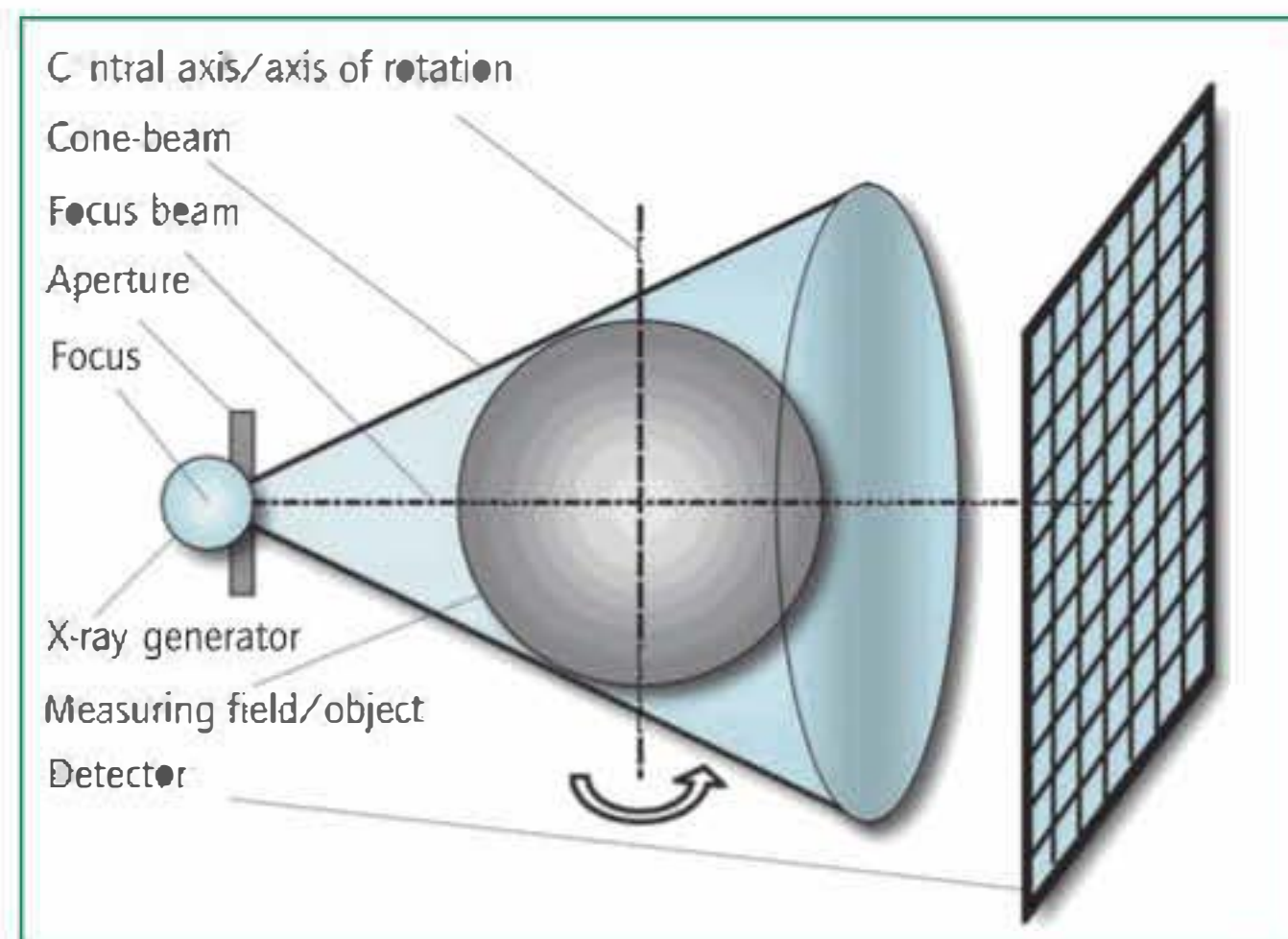


Fig 1-13 Diagrammatic representation of the exposure geometry and the essential components of a CBVI system.

In a further step, the maximum permissible cone-beam is precisely defined by a fixed aperture. The tubes currently used in both CBVI and CT are very compact so-called single-tank x-ray tubes, integrating the high-voltage generator in the tube housing.

The information content obtained during imaging is determined by the type of image detector and the kinematics of the object (movement, arrangement of the tube assembly/image receptor). In a panoramic system with a one-dimensional line detector, a 2D projection image (panoramic view) is produced by rotation around the object. In CT, a fan beam produces a one-dimensional image of the object at the detector, and a 2D slice through the object is generated by rotation. A 3D volume can be compiled via secondary reconstruction by displacing the imaging system or the object and generating additional slices.

The cone-beam geometry of the CBVI systems permits the direct generation of a “genuine” 3D volume data set of the object using a 2D detector and a single 180 degree rotation around the object. During the scan, the x-ray tube generates x-rays shaped into a cone-beam and emitted in short pulses, which then impinge on the object to be imaged. The detector (sensor) behind the object being imaged registers the individual projection images. The detector thus creates 2D projections of the object from different viewing directions. A 3D image volume can be computed directly from these, using 3D image reconstruction algorithms.

At the present time, there are two different detector types for 2D imaging: the image intensifier system and the flat panel detector (also called solid-state detector). Both systems are digital imaging systems: they acquire the individual 2D projections in individual pixels that can be further digitally processed. Depending on the system, there are 250,000 to 1,000,000 pixels per single projection, which typically have to be read about 20 times per second during a scan. The dynamics for reading the detector contents must be set up accordingly. By grouping together several adjacent pixels (binning) during imaging, the scanning rate can be improved (reduction of scanning time), but once this is done, the 3D volume can no longer be computed in its full resolution.

Image intensifier systems function using an electronic intensifier system, which is connected upstream to the actual digital detector (CCD camera). The x-ray quanta are initially converted to electrons on the input screen, which are accelerated to approximately 30,000V and then displayed on another screen. This screen converts the electrons to light quanta. The total amplification factor is approximately 10,000. The light quanta are now optically depicted on the downstream CCD camera.

Flat panel detectors occur as direct and indirect systems at present. In the indirect systems, a converter layer made of scintillator material (generally CsI) converts the x-ray beams to photons, which are then passed on via a photodiode layer to a readout matrix (generally made of amorphous selenium). In the direct conversion systems, the x-ray beams are usually directly converted into electrons by a layer of amorphous selenium; the electrons are then conducted to the readout matrix. Significant research activity is currently examining methods to optimize the conversion, the readout matrix and the coupling of the two, aimed at further improving the systems and their economical implementation.

The images produced by either detection system require a series of corrections prior to further processing to reconstruct the 3D volume data set. In the image intensifier systems, distortions of the raw data by electromagnetic influences in the intensifier chain must be corrected; in the flat panel detector systems, corrections must be made for missing lines and pixels as well as temperature influences. In both systems, the individual pixels must be matched to the sensitivity of the readout unit. Ultimately, both systems deliver undistorted projection images and, after reconstruction, a geometrically accurate volume, in which distances and angles can be correctly measured.

The quality of the image system is affected by several factors, the most important of which are resolution and contrast. Both are combined in the MTF, since they are closely associated with each other. The pixel size of the detector and the resulting voxel size of a CBVI image volume does not necessarily correspond to the resolution.

Since the natural purpose of imaging is to deliver the best image signal at the lowest dose (patient exposure to radiation), another important parameter describes the relationship between the actual image signal and the noise signal of the system. This is called the quantum yield (signal-to-noise ratio, SNR). The detective quantum efficiency (DQE) is given by $[(\text{SNR}_{\text{out}}) / (\text{SNR}_{\text{in}})]^2$ where in and out refer to the input and output of the detector. Besides depending on resolution and contrast, the DQE of an imaging system is also a function of dose and the system's age. At present, flat panel detector systems have the better DQE at higher doses, while the image intensifier systems are advantageous at very low doses. This physical property of the detector has a clinical impact on the effective dose given to the patient. Current publications indicate that systems using the image intensifier require less dose than systems using the flat panel technology. In some countries, this is an important aspect since the indication for 3D imaging has to be in positive risk benefit ratio.

Along with these important parameters, artifacts, which occur in all imaging systems (including CT, CBVI and conventional panoramic imaging systems), also influence image quality. Sophisticated calibration methods available in some CBVI systems permit the use of cone-beam technology with almost any conceivable geometry. As a result, the axis of image generation (x-ray tube/detector) can be tipped out of the rotational plane (perpendicular to the axis of rotation). Artifacts in reconstruction of the volume data set consisting of the individual projection images can thus be reduced. In addition, the configuration can be better adapted to the anatomy and the detector can be guided closer to the object, resulting in an increased volume that can be visualized.

Effective integration of the new CBVI systems into dental practice will be challenging because of the large data volume. Depending on the system, the data volume of a scan is between 200 and 1000 MB. The information must be stored in such a way that it can be efficiently accessed for a specific time frame and that it (or a relevant extract) can be archived in the long term for legal purposes. In medical clinics, so-called picture archiving and communication systems (PACS) are available for the 3D imaging systems of radiology (CT, MRT, etc.). Manageable and cost-effective systems must now be provided for use in dental practice. The rapid developments in the fields of memory modules, image compression algorithms and computer systems are bringing this goal closer.



Fig 1-14 2D visualization of the CBVI volume data in the three orthogonal principal planes. From left to right: axial plane, sagittal plane and coronal plane.

1.6 Visualization of the Data

Diagnostic effectiveness is crucial for any dental practice. Therefore, the essential information in each scan has to be visualized clearly to be readily understood. Ideally, software will have an intuitive user interface so assistants can prepare the data set and clinicians can access the relevant information as quickly as possible. As CBVI data are in digital form, they can be further processed for direct display by the computer. Density values, histograms and other tissue parameters and geometric values can be determined at any time – CBVI systems generate volume data that are geometrically accurate: the anatomy can be visualized in true dimension and, therefore, be measured one to one.

For a suitable overview, 2D or 3D images can be generated from the original image volumes, but 2D slices have proven to be most effective for detailed diagnosis. The 3D image volume is, therefore, generally first visualized in the three orthogonal principal planes (axial, sagittal and coronal planes (Figure 1-14)).

However, 3D visualization of volume data is also an important aid to clinical diagnostics. As early as 1989, the use of 3D image visualization was studied clinically in a prospective trial.¹¹ In 90% of the total of 150 patients studied, 3D image visualization was rated therapeutically useful by the treating surgeons. Particularly in the field of maxillofacial surgery, 3D imaging of the cranium provided a better spatial impression of bone destruction and thus a better appreciation of the patient anatomy and pathology. Numerous methods have been developed to achieve the best visualization of anatomical structures in different applications. There are volume-based and surface-based processes, each permitting a different representation of the volume images and consequently complementing one another.

- Volume-based visualization techniques permit the semitransparent visualization of the entire image volume and allow an insight into the “inside” of the object. A wide range of information can be interactively extracted from the data volumes, for example to provide information about the architecture and complexity of individual structures.
- Surface-based visualization processes only permit visualization of the object surfaces – information about the inner structures is not available. The objects to be visualized must first be segmented and their “outside” approximated by geometric parameters. However, the extracted object surfaces can be visualized very efficiently.

Using 3D visualization, the physician can display the patient data as a whole immediately after imaging and can interactively hide or display specific structures to acquire an initial impression of the anatomy (Figure 1-15).

Both 3D and 2D visualizations in the principal planes enable easy orientation but are not directly oriented to the anatomy. The visualization of user-defined curved surfaces offers an essential advantage. From the CBVI data, views can be synthesized that are perpendicular to the midline through the jaw defined in the transverse plane, as in Figure 1-16.

If this synthesized view is expanded to sum the x-ray attenuation values over a specific area transverse to the midline of the jaw, the resulting views approximate the image impression of a so-called panoramic image (Figure 1-17) – a special technique in x-ray panoramic tomography.

An essential advantage of the CBVI technique is that regardless of the examination method, different views can be retroactively synthesized from the volume data and combined at will. Figure 1-17 shows both the view that is similar to the image impression of a panoramic image and a smaller image extract (outlined in blue) that shows a visualization without superimposition at an arbitrary distance from the midline of the jaw.



Fig 1-15 3D visualization of the CBVI volume data; left: volume-based method, right: surface-based method.

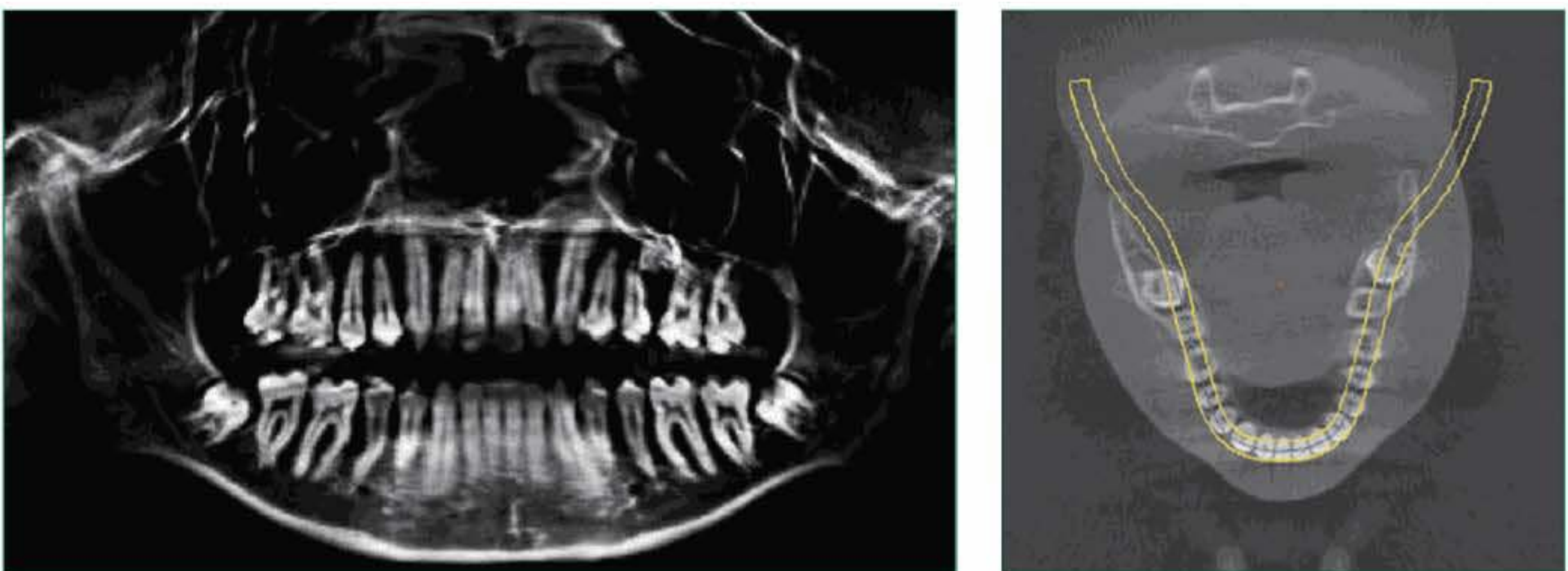


Fig 1-16 Synthesized view along the midline through the jaw.

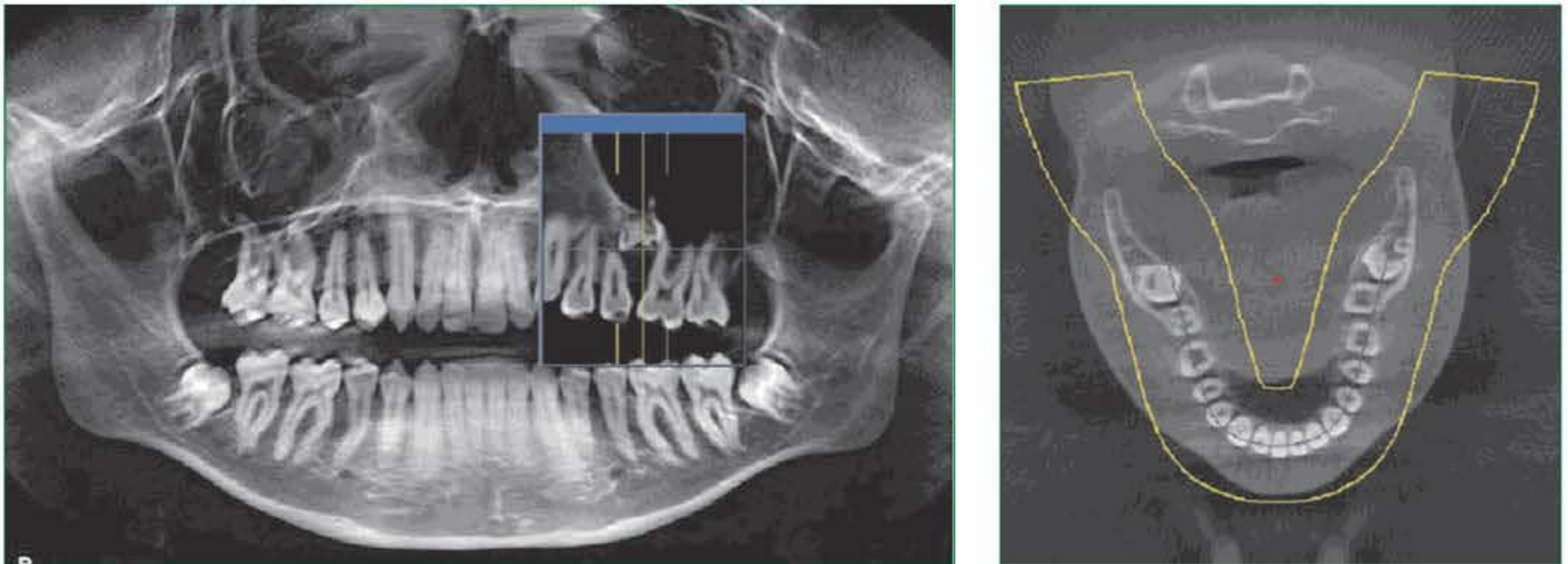


Fig 1-17 "Panoramic tomograph" and image detail (blue) with visualization without superimpositioning.



Fig 1-18 Left: secondary section transverse to the midline of the jaw; right: detail visualization along the midline of the jaw in increased resolution.

In addition to the "panoramic image", a series of regularly spaced secondary slices can be created transverse to the midline of the jaw, which facilitates the decision of whether and how a jaw implant can be placed (Figure 1-18).

These views synthesized retrospectively from the CBVI data can thus have any curvature and tilt angle and depict summations of the x-ray attenuation values at any depth orthogonal to the predefined line of curvature. This optimizes the creation of dedicated visualizations for each type of examination. Special views that are comparable to a cephalometric radiograph, for example, can be computed from the recorded CBVI volume data at any time (Figure 1-19).

With such a variety of visualization options, it is important to ensure that the application chosen provides the physician with the ideal views for the type of examination, thus enabling effective diagnosis and treatment planning (Figures 1-20 and 1-21). It is also vital that the various synthesized views are interlinked so that the best views and information can be chosen for the anatomy and the problem of a particular patient. This type of dynamic diagnosis in different views also requires an interactive visualization of 2D and 3D visualizations; only then can the 3D CBVI volume data be intuitively utilized and intelligible on a 2D display monitor. Figure 1-20 shows two such combined visualizations from synthesized single views.

An optimized combination for dental applications consisting of single views is shown in Figure 1-21 and provides a high degree of integrated visualization.



Fig 1-19 Cephalometric radiograph synthesized from CBVI data.



Fig 1-20 Two combined visualizations from four and seven synthesized single views, respectively.

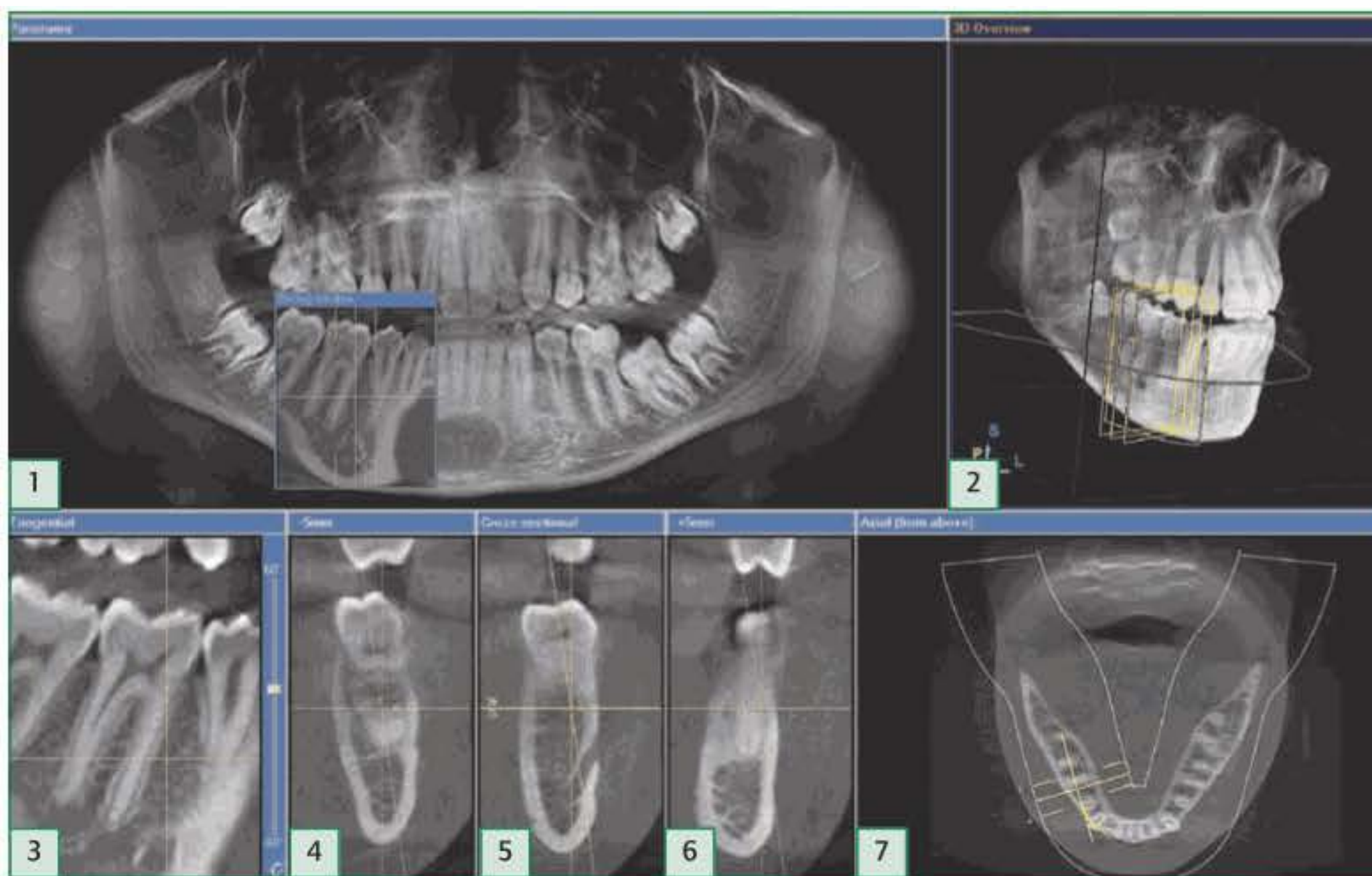


Fig 1-21 Integrated visualization of a 3D volume data set from slice, volumetric and reconstructed summation images.

(1) The orthopantomograph computed using a freely definable panoramic curve provides an overview. Within it, a single slice can be visualized using the examination window (2) parallel to the panoramic curve. Synchronous to this examination window, the lower series presents a tangent (3) and transverse slices (4, 5, 6) at 5 mm distances from the panoramic curve.

The tangent can also be tilted, in order to orient it parallel to any tooth axis. Depending on the position of the examination window, these slices assume a coronal or a sagittal orientation. In addition, an axial slice (7) and a volumetric 3D view of the data set are presented for orientation purposes. The position of the other slices can be seen as yellow lines (GALILEOS, Sirona, Bensheim).



Fig 1-22 Visualization of various single views intended for implant planning. In the implant view, the tomograph can be rotated around the implant axis.

1.7 Application Software for Cone-beam Volumetric Imaging Systems

The wide range of possibilities illustrated in the previous section for generating synthesized single views from the 3D CBVI data open up a multitude of opportunities for creating dedicated end-user applications optimized for the examination type. Figure 1-22 shows one example of such a special application, siCAT's implant planning software, GALILEOS-Implant.

1.8 References

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2 Image Quality: Requirements and Influencing Factors

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Today, imaging systems have a significant influence on diagnosis and therapy in dental and oro-maxillofacial medicine. Therefore, for the treatment provider, it makes sense to demand the best image quality possible from an imaging device. Of course, this also applies to cone-beam technology, with several special considerations in image quality assessment.

Cone-beam technology is a relatively new method that first entered dental, oral and maxillofacial medicine as recently as 1998.¹ Consequently, experience with large data sets is only available at a few centers. However, such experience is needed in order to assess the capabilities and limitations of this new imaging method with confidence.

The purpose of this chapter is to familiarize the reader with the subject of image quality in cone-beam technology, to formulate the minimum requirements imposed on image quality and to explain the corresponding influence factors.

2.1 Definition of Image Quality

The image quality of a system can be considered technically or scientifically, but the parameters used for this are generally difficult for the treatment provider to apply in practice. Nevertheless, these parameters provide a basis for an understanding of radiological systems and will, therefore, be discussed in more detail.

The quality of a radiograph is defined as the property of transferring the attenuations of the x-ray beams in an object to be imaged as accurately as possible into a perceptible image.² The three parameters of image quality are contrast, sharpness and noise.

2.1.1 Dynamic Range/Detector Contrast

The **dynamic range** is the dosage range that can be converted into intelligible data by a digital detector. It approximately corresponds to the contrast response of film-foil systems. For practical determination of the dynamic range, different radiation doses are assigned to their corresponding density, and a density curve is generated.

The **contrast** describes differences in dose, brightness or intensity in an image. Without contrast, a structure cannot be differentiated from its surroundings. In addition to the detector-specific properties, x-ray beams influence contrast. The beam effects are determined by different physical properties of the x-ray beams and the density of the structures to be visualized. This includes quantum noise, beam quality, object absorption and scattered radiation. The relevant radiological literature will have a more complete discussion of these general principles. In digital radiological systems, the contrast at the time of actual imaging must be differentiated from the contrast of the visualization on the monitor.

The majority of digital radiographic systems can record and display an image range of 1024 to 4096 gray levels. However, an observer can perceive only 20 to 35 different grays owing to the limitations of human vision. Therefore, the image range of a digital image that is usable by the observer is less than that actually contained in the image. However, in digital systems it is possible and necessary to use the contrast and brightness functions in the software to appropriately adjust the gray level range of interest for examination of the digital data set. This process is called *windowing*. Here, the gray levels of interest are placed in a window and displayed accordingly, while the levels outside of the window are masked.² Using the appropriate adjustment of contrast and brightness within this window, low image contrasts can also be increased and high contrasts can be attenuated.³ However, when adjusting contrast and brightness, it should be noted that gray level range and contrast have a negative correlation, since many different gray shades and thus small differences in gray levels cannot be perceived at higher contrast levels.

2.1.2 Sharpness

The term **image sharpness** refers to the quality of the transitions between the different densities, for example between pulp and dental substance. The sharper the image, the more defined the signal contours are. The sharpness impression of the image depends on the size of the details and on its contrast, contrast gradient, spatial resolution and noise.³ High-contrast objects often subjectively appear sharper than objects with low contrast.

The (local) resolution capability is defined as the discrimination between two structures and can be indicated in line pairs (LP) per mm. The more line pairs that can be represented per millimeter, the greater the resolution capacity. A value of 5 LP/mm means a resolution capacity of 0.1 mm. The spatial resolution can be determined using a lead line pattern (e.g. Figure 2-1).

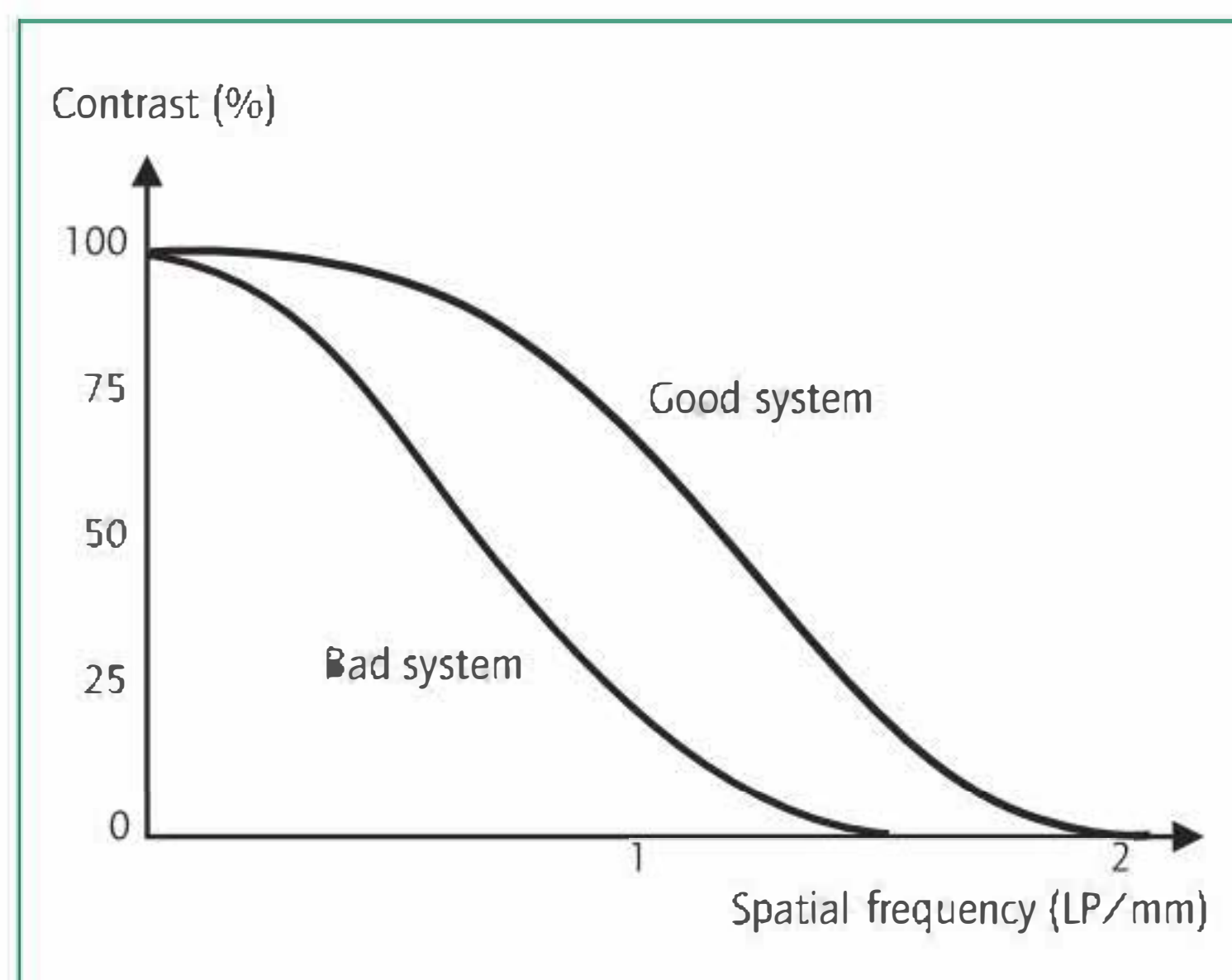


Fig 2-1 Diagrammatic explanation of the modulation-transfer function.

Object movement during imaging and the technical imaging response of the detector have an adverse effect on image sharpness and resolution capacity. As the resolution response in line pairs is determined by a human observer and is thus subject to a subjective component, the modulation-transfer function (MTF) was introduced to increase objectivity. It measures the transfer of a sine wave-shaped modulation of the object contrast into image contrast.

$$\text{MTF} = \frac{B(f)}{O(f)}$$

where B is image contrast; O is object contrast; and f is the spatial frequency of the modulation.

Accordingly, the MTF is a mathematically exact description of spatial resolution that is independent of subjective factors. This function is applied to routine inspection of the quality of an x-ray machine.

2.1.3 Noise

Image noise in digital systems is made up of quantum noise and system noise. Quantum noise is caused by the fluctuation of the x-ray beams, which results in small variations in the density of the quanta. Noise in the detector is caused primarily by the signal amplifier and the analog–digital converter. At low doses, quantum noise predominates, but it diminishes with increasing dose and the effects of intrinsic noise become more apparent.⁴ Image noise reduces the recognizability of small image structures. Overall, in digital systems, noise decreases with increasing applied dose.

An important parameter for identifying the performance of an x-ray detector is the detective quantum efficiency (DQE). It describes how efficiently an x-ray detector can convert the radiation present at the detector input into a digital image. The DQE is defined mathematically and physically by the quotient of the squared signal-to-noise ratio at the output divided by the squared signal-to-noise ratio at the input. This results in a value between 0 and 1, where 1 means a complete conversion of all x-rays impinging on the detector into an image, and 0 means that the detector cannot display the image information at all.

2.2 Methods for Evaluating Image Quality

The methods described above are rather technical and are used in the objective determination of image quality. In addition, there are quasi-objective as well as subjective methods that can be useful and these will be briefly explained here.

Objective methods for quantifying image quality are based on the measurement of physical parameters. They are characterized by high accuracy and reproducibility. They include the determination of the dynamic range of an x-ray system, for example.

Quasi-objective methods involve evaluation by an observer. Examples are spatial and contrast resolution.

2.2.1 Subjective Methods for Quantification of Image Quality

The measurement of subjective parameters takes into account the influence of the human observer and the observation conditions, which have a fundamental impact on image quality.^{4,5} Discernment of structures in an image is limited by sensory physiological perception processes such as the stimulus threshold, spatial resolution, contrast perception, adaptation, integration and display times as well as the motion threshold.² **Receiver-operating characteristic (ROC)** analysis is one subjective measurement method. It examines the sensitivity of a method as a factor of specificity. Using a confidence scale, the examiners indicate their level of certainty regarding the presence of a lesion. ROC analysis permits an estimate of the diagnostic performance of imaging methods⁶ and offers a practical means to evaluate the clinical value of an imaging unit.

Statistically analyzed examinations of cone-beam technology have confirmed its benefits for implantological and oral-surgical diagnostics.^{7,8} In addition, model studies indicate that detection of carious lesions is possible.⁹

2.3 Image Quality Requirements

Requirements for imaging systems can be found in the quality guidelines of the German Medical Association¹⁰ and include the following.

Characteristic image features describe organ-typical image elements and structures that should be satisfactorily discernible and recognizable in the x-ray image of a body section when typical projections are selected.

Important image details show the dimensions of individual structures and sample elements in the x-ray image that have essential diagnostic significance as characteristic parts of the overall image and should be represented with sufficient clarity. They are, in part, the result of multiple superimpositions of smaller anatomical substrates that are not directly depicted.

Critical structures accentuate the features of the x-ray image that are important to the diagnostic statement and are representative of the quality of the image.

These requirements have been applied to previously established imaging modalities and so far have not been established for cone-beam technology. The requirements for intraoral x-ray, cranial postero-anterior (PA) and antero-posterior (AP) radiography and cranial CT imaging are used here as a general basis for the requirements for the cone-beam method. Regarding the requirements proposed in the following text, it should be noted that these are analogous to those requirements set out for radiology and imaging by the German Medical Association:

"The quality of radiological diagnostics is determined by a critical medical indication with an established purpose, optimized performance of the examination, depiction of the diagnostically important image information with medically justifiable low levels of radiation exposure and expert interpretation of the examination and of documented results in the report on diagnostic findings. The guidelines include medical quality requirements, recommendations for the imaging technique and the physical and technical parameters of the image generating system with which satisfactory diagnostic quality can be obtained. These guidelines describe the current medical standard and the current state of technology of basic radiological examinations."

2.3.1 Derived Requirements for Cone-beam Imaging in Dental, Oral and Maxillofacial Medicine

Characteristic image features:

- depiction of the bone structures of the visceral cranium, vertically from the chin to at least over the orbital floors and horizontally from the apex of the nose to at least the complete representation of the sella
- depiction of the soft tissue contours of the anterior visceral cranium
- assessability of air-filled compartments and osseous structures in the image area
- complete depiction of the individual teeth, including the coronal and apical regions
- size-appropriate depiction without superimpositioning
- visually sharp border of the alveolar-inner cortex
- representation of the regionally typical bone structure of the jaw.

Important image details:

- with representation of bone changes ≤ 2 mm
- with representation of dental changes ≤ 2 mm.

Critical image elements:

- evidence of defined shape and density changes, integrity of the osseal elements, especially of the walls in the paranasal sinus image
- apical region
- proximal walls of the dental corona
- alveolar wall
- interdental space
- bone structure of the jaw.

2.4 Factors Influencing Image Quality

2.4.1 Physical Factors

The image quality of an x-ray-based imaging system primarily depends on its design and on the characteristics of the components used. The underlying physical principles apply to all x-ray devices and will, therefore, not be discussed in detail here. The interested reader is referred to the relevant radiological literature and to Chapter 1.

However, the following physical factors for achieving optimum image quality are briefly listed.

1. Optimum optical density and Wiener spectrum. The Wiener spectrum is measured by determining the fluctuation of the optical density of a uniformly irradiated x-ray film. The square fluctuation of the optical density is plotted as a function of spatial resolution. In digital systems, there is no direct relationship between dose and optical density of the x-ray image.
2. Minimization of motion blurring. Sufficient stabilization can be achieved using a short exposure time with increased dose rate. Dose rate can be increased by an increase in the tube voltage, increased focus or by increasing the power output (greater preheating of the cathode; drawback: shorter tube life).



Fig 2-2 Reclining position in the NewTom unit.

3. By satisfactory contrast. Variation of the beam energy (in kilovolts).
4. Minimization of geometric blurring. Reduction of the focal spot size and/or of the object–film distance and increase of the focus–object distance.
5. Reduction of scattered radiation. Collimation, grid, compression.

2.4.2 Patient Positioning

In cone-beam imaging, the patient may be in a reclining, sitting or standing position, depending on the particular manufacturer's equipment type.

The advantages of the reclining position, such as in the NewTom device (Figure 2-2), include the possibility of examining a severely injured patient. In addition, the reclining position is comfortable for the patient. However, its drawback is the need for greater floor space, which is not available in every practice. In addition, the unit is of limited use for claustrophobic patients because patients lie within a tube. The motor-driven final positioning using the berth is comfortable but also time consuming. The greatest drawback is the limited applicability of a reclining position for orthodontics, since images must be made in an upright position.

Seated positioning has the advantages of a lower floor space requirement and a stable positioning for all patients except the severely injured. However, in fixed installations such as the Hitachi MercuRay (Hitachi, Tokyo, Japan), the Accuitomo (Morita, Japan) or the i-CAT (Imaging Sciences, Hatfield, USA) units, patients using wheelchairs must be transferred and the sitting position must be adapted to the respective physique using motors, which requires a greater time investment.

A third option is a flexible solution that allows imaging both in the standing and in the seated position (Figure 2.3). For example, Sirona's GALILEOS unit is used mainly in the standing position but can also be used with a patient sitting in any chair, for example a frail patient. Patients using wheelchairs can also be easily positioned, thus eliminating an inconvenient transfer. The height of the entire x-ray unit, consisting of the suspension, radiation source and imaging detector, can be infinitely adjusted to provide this flexibility.



Handling of the unit is efficient as it is part of the panoramic radiography unit. However, the patient's head must be held steady during imaging; a suitable occlusal appliance with an accessory forehead support pad serves this purpose.

Positioning of the patient for imaging is mainly dictated by operational considerations in the practice but upright positioning is important in orthodontics. The patient should be in the most relaxed and comfortable position possible to obtain the most stationary image.

2.4.3 Duration of Imaging

The duration of imaging is a critical parameter for image quality. This is well known in CT and MRI, where increasing imaging duration can create movement artifacts that exceed a critical limit.

The heart of the problem is that, when reconstructing the 3D volume using 200 or more individual images, any movement of the patient during imaging causes the recording of different object positions in the volumes. This results in double contours (see Figure 2-7) in the reconstructed volumes. Therefore, it is generally recommended that the imaging duration be kept as short as possible: less than 20 seconds is recommended. According to studies by Heiland *et al.* (2004)¹¹ and Holberg *et al.* (2005),¹² an imaging time of 78 seconds results in relevant movement artifacts in up to 20% of cases. In contrast, studies with the GALILEOS scanner using a scan time of 14 seconds demonstrated a marginal effect of movement artifacts on image quality in only 6.55% of patients.

Fig 2-3 Positioning options. A sitting position is used for the i-CAT (a) and Accutomo (b) whereas the GALILEOS (Sirona) (c) is a flexible occlusal appliance design for imaging in a sitting or standing position.

2.4.4 Scanning Parameters

As described above, image quality is influenced by the object or patient characteristics on one hand and by different device characteristics and settings on the other. To obtain consistent image quality with variable objects while generating the lowest possible radiation exposure, some of the device parameters must be adapted to the individual patient. For example, the different radiation absorption functions of underweight and overweight patients or of children and adults can be taken into account. Possible practical adaptations involve the beam energy/hardness, the quanta and the exposure time.

The voltage applied to the x-ray tube determines the energy and thus the penetration power of the x-ray beam, which is also referred to using the term "hardness". The higher the voltage at the x-ray tube, the more energy rich and short waved is the generated radiation. Low-energy radiation is referred to as "soft" x-ray radiation.

The current strength (in milliamps) set on the x-ray unit determines the quantity of electrons emitted at the cathode and accordingly the quantity of x-ray radiation. In addition, the radiation quantity can be influenced by the duration of the x-ray current flow. In this context, the term "milliampere second product" (mAs) is also used.

For the purposes of radiation protection and avoidance of movement blurring, the shortest possible exposure to x-ray radiation is desired.

To make the overall handling as simple as possible for the user, it makes sense to use the factory settings for the relevant indication, which allow simple adaptation to the different patient types. When properly selected, these presettings permit the optimization of image quality together with the lowest possible radiation exposure.

Overall, cone-beam visualization results in a comparatively low radiation exposure. This becomes obvious in direct comparison with CT. While the radiation exposure in spiral CT can be significantly reduced by reducing the exposure time and the specific collimation of the volume to be depicted, it is still significantly higher than the radiation exposure in cone-beam imaging. Several reference values from actual examinations are listed for direct comparison in Table 2-1.

Image modality	Effective dose (μSv)
Orthopantograph digital	6.2 ¹³ ; 5–14 ¹⁴
Orthopantograph conventional	10 ¹⁵ ; 16–21 ¹⁴
Transverse slice acquisition	3–12 ⁸
Conventional tomography	2–9 ¹³
Cone-beam	36.3 ¹³ ; 50.3 ¹⁶ ; 105 ¹⁴
Low-dose computed tomography	150–610 ¹⁵
Conventional computed tomography	314 ¹³ ; 600 ¹⁷ ; 1270 ¹⁵

Table 2-1 Overview of different effective radiation doses in dental radiological diagnostics.

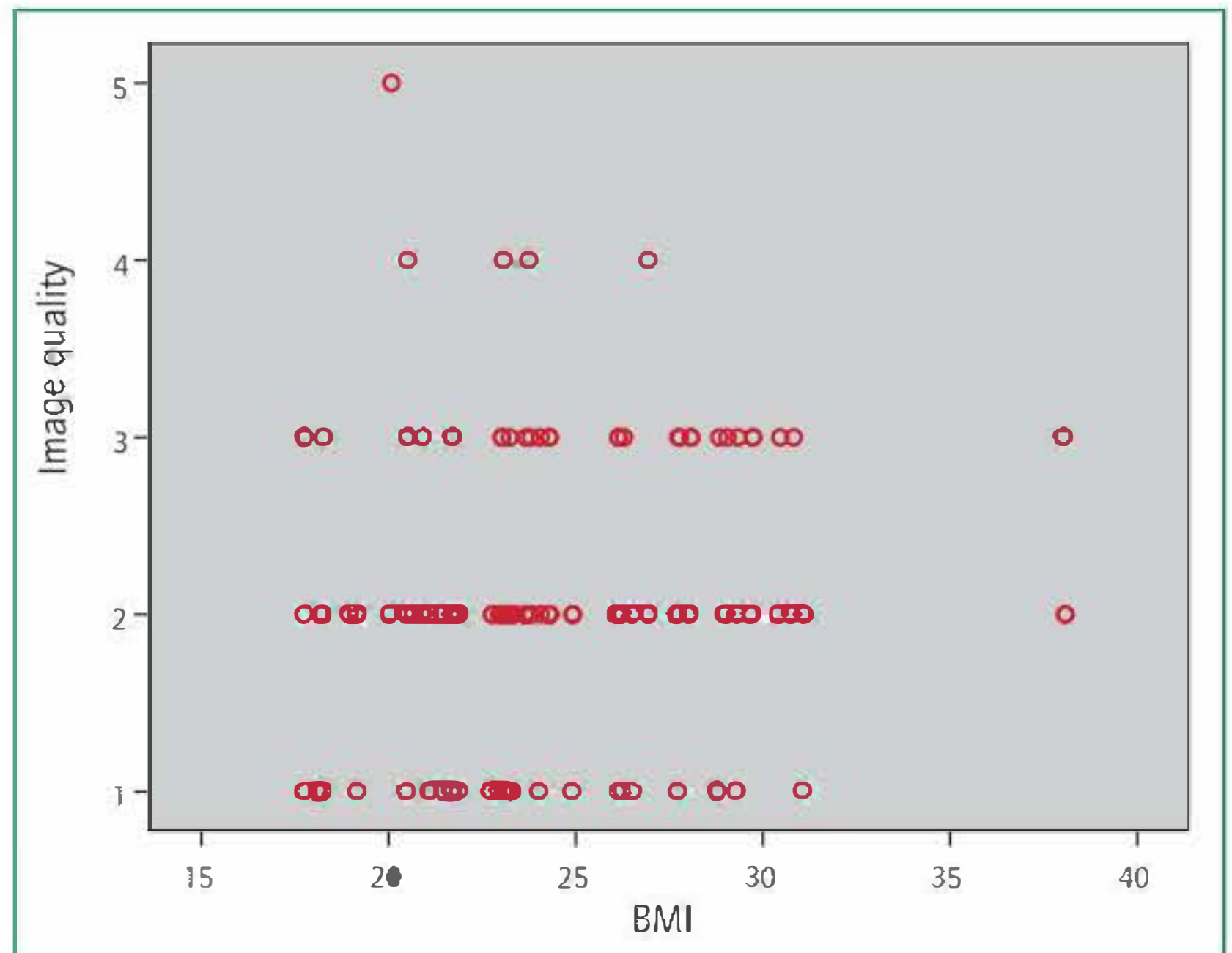


Fig 2-4 Scatter plot of the distribution of body mass index (BMI) and image quality (rating scale 1 to 5, excellent to poor) using the GALILEOS system.

2.4.5 Body Mass Index

Since image quality also depends on the object to be depicted, specific settings may be required for imaging obese patients. The body mass index (BMI), a widely used measurement for identification of obesity and hence of body mass, was, therefore, used as a modulating factor to examine image quality in cone-beam radiography (Figure 2-4). The BMI was originally introduced by insurers for risk management applications but is today accepted as a characteristic value in many medical publications. It is computed using the following formula:

$$\text{BMI} = \frac{\text{weight (kg)}}{\text{height}^2 \text{ (m)}}$$

Particularly in the USA but also in Europe, there is a trend toward more overweight persons in the population, making this an issue of increasing importance for the dentist.

However, according to studies using the GALILEOS system, no adaptation of scan parameters is required in cone-beam imaging as no correlation was found between the BMI of the patient and the perceived image quality (see Figure 2-4).

2.4.6 Age

Patient age has not been directly identified as a factor influencing image quality, but certain age-related factors have been. Two considerations appear particularly significant to radiological imaging. First, the cooperativeness of very old and very young patients is sometimes limited, which can compromise imaging. Second, the number of metallic restorations in the mouth increases with increasing age, which results in a higher incidence of metal artifacts.

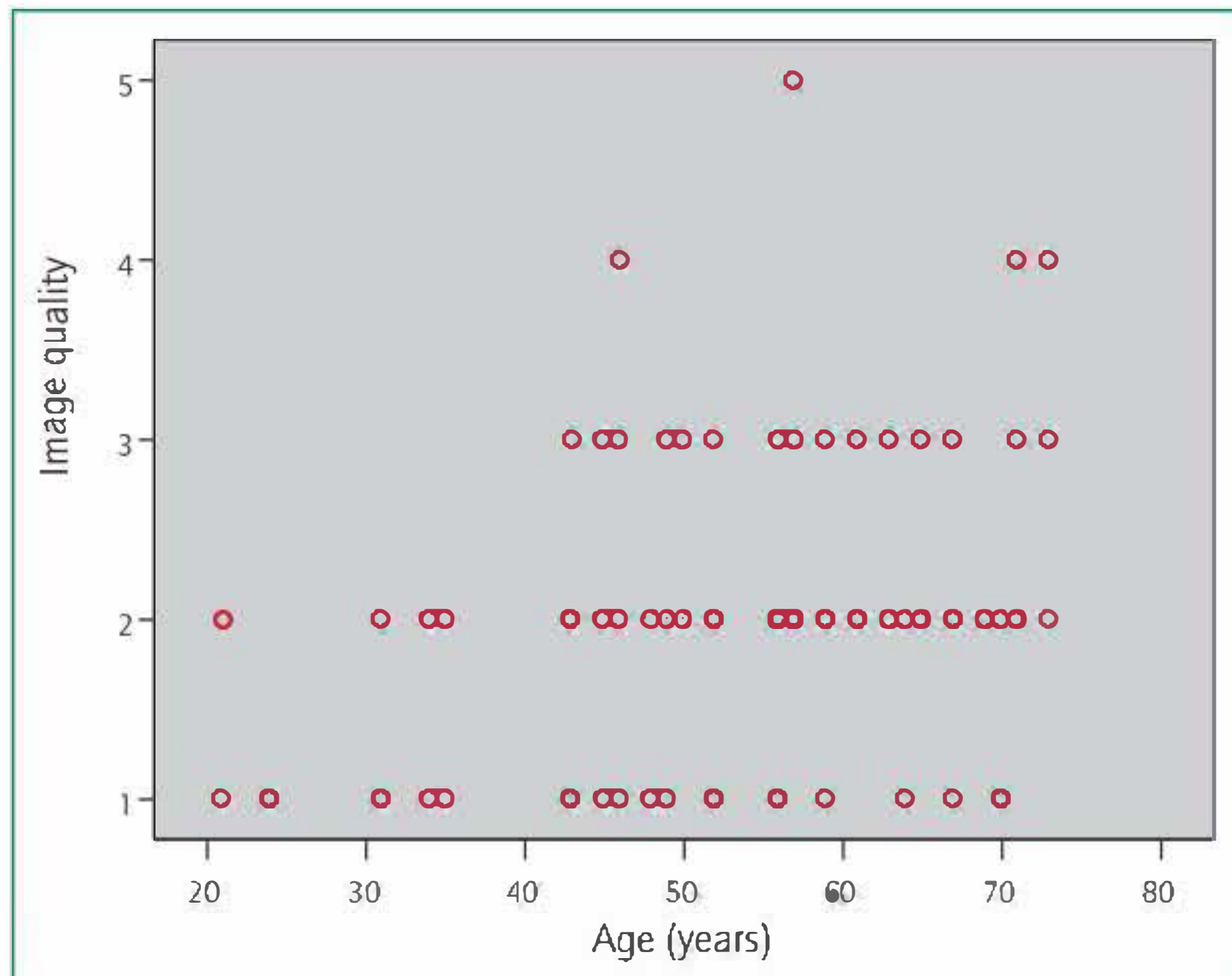


Fig 2-5 Scatter plot of the distribution of age and image quality (rating scale 1 to 5, excellent to poor) using the GALILEOS system.

Studies have shown that cone-beam image quality correlates negatively with patient age (Figure 2-5).¹⁸ While this correlation is statistically significant, no unusable images were found even in patients over 70 years of age. Therefore, cone-beam imaging should be considered appropriate for all elderly patients as well.

2.4.7 Metallic Restorations

The long-term use of metallic materials in dentistry means that artifacts caused by metallic restorations in the mouth cannot be ignored entirely when utilizing cone-beam imaging, especially with fixed restorations, amalgam fillings or telescopic restorations. Artifacts arising from the presence of metal in the mouth are of two types.

1. A black center will appear within the metal-dense object if the density of the object exceeds the numerical range of densities that can be visualized in the cone-beam method.
2. Streak artifacts arise from the computed backprojection of beams incapable of adequately penetrating very dense materials such as those containing metals, where high-energy photons will be absorbed at the atomic nucleus. In this case, the x-ray detector registers that no radiation was transmitted for that area. A zero computation arises for those beams and a significant difference arises relative to adjacent beams, which is manifested by streaks on the computed image.

While certain alterations, such as movement artifacts, affect the complete data set, metal artifacts are streak shaped, with their metallic cause in their center. These artifacts are local and propagate in the data set mainly horizontally, along the x-ray radiation path at the time of imaging (see Figure 2-6). Accordingly, these metal artifacts are most frequent in direct proximity to larger metallic restorations and in their horizontal layers. To minimize this effect, a special inclined geometry of tube assembly and imaging detector can be used (e.g. in the GALILEOS system), which projects any metal artifacts out of the occlusal plane. Even for anatomical structures significant in oral surgery, no relevant influence on the diagnostic value of GALILEOS cone-beam images was determined to be attributable to metal-dense materials in fillings, crowns, bridges, post-and-core systems or implants.⁸

In comparison, metal-dense objects in the x-rayed volumes in CT result in a greater compromise of image quality than in cone-beam imaging.¹² In general, the influence of metal-caused streak artifacts can be reduced using mathematical reconstruction algorithms.

2.5 Examples of Artifacts and Unsatisfactory Images

This section will give several examples enlarging on the factors influencing image quality described above. In practice, with optimally adapted scanning parameters, metal artifacts will be the most likely causes of reduced image quality. Especially for inexperienced examiners, they make it harder to differentiate pathological processes that are usually demonstrated as bright spots in the dental or osseal area of the artifacts. In certain patient populations with limited ability to cooperate, relevant movement artifacts can also affect image quality.

2.5.1 Metal Artifacts

The generation and appearance of metal artifacts has already been discussed in Section 2.4.7. Figure 2-6 illustrates the influence of radiopaque metallic fillings and gold crown reconstructions on the depiction of the mandibular posterior dental region. The center of the cross-hairs in Figure 2.6 locates a point that can be seen in all three orthogonal layers. The metal itself appears radiopaque here. During cone-beam imaging, streak-shaped artifacts form along the x-ray path around the radiopaque center of mass. They can be observed in the orthogonal depictions as streaks that almost exclusively expand horizontally. In the sagittal and coronal depiction planes, it is obvious that there is no cranio-caudal expansion of the streaks. Furthermore, in the sagittal view, a cancellation artifact can be seen in the area under the mesial crown margin of tooth 46. This effacement cannot be attributed to any morphological correlate. All information in the 3D data set is missing for this area owing to the extreme attenuation of the x-ray beam upon penetrating the crown material. Consequently, this area cannot be diagnosed regarding whether it is a carious lesion.

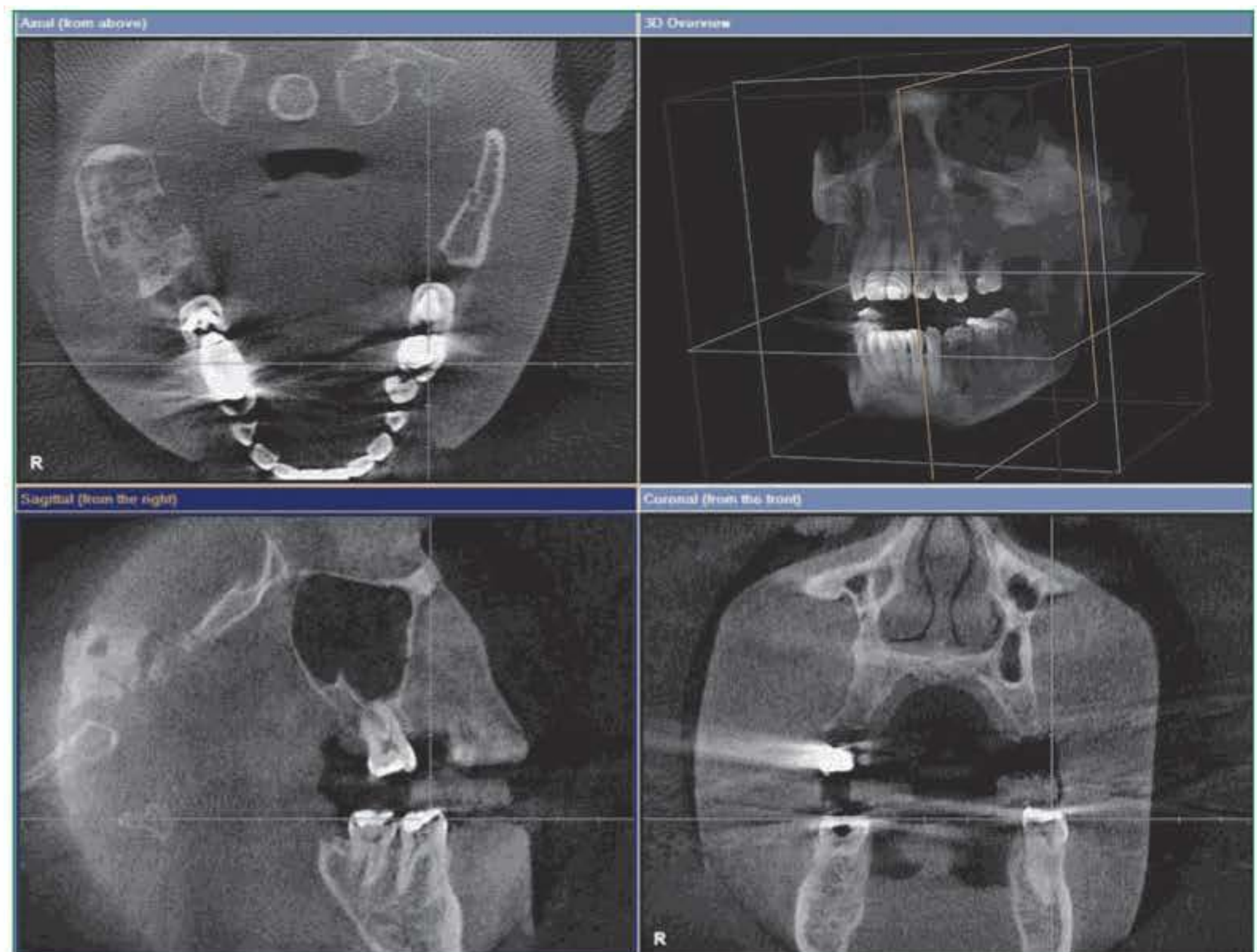


Fig 2-6 The influence of metal-dense structures on image quality. Along with the clearly recognizable metallic crowns, conspicuous lucencies in the coronal region of teeth 36 and 37 can be observed. These are metal artifacts and not caused by carious processes.

2.5.2 Movement Artifacts

The causes of movement artifacts have been described above. The cone-beam image of a 19-year-old male patient is shown in Figure 2-7; he was stabilized in the x-ray unit using a chin rest in the context of an orthodontic diagnostic procedure. Merely supporting the head near the point of the chin stabilizes the head significantly less than using an occlusal appliance tightly squeezed between the rows of teeth in the occlusal plane. The image shows the consequences of patient movements during imaging. This is recognized by the double contours extending over the entire data set. Movement artifacts are particularly noticeable in the transition area between tissues of different densities. For example, the border of dental pulp and calcified dental substance cannot be recognized as a distinct transition. Consequently, the patient's movement during imaging also influences spatial resolution and the discrimination between different structures. Movement artifacts have only a minor influence on the overview character and on larger findings. In contrast, if the examination of fine marginal structures is of importance, they make the diagnosis significantly more difficult. Particularly in cariology and periodontology, this can be problematic and result in manifest limitations of the diagnostic value of a cone-beam image. In other words, patient cooperation and sufficient stabilization are crucial, particularly in areas that require a high degree of spatial resolution.



Fig 2-7 The 3D reconstruction of a cone-beam data set (upper right) and the depiction of the three orthogonal planes. The influence of patient movements during imaging can be seen as double contours in the orthogonal planes, particularly in the anterior cranium.

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Diagnostics

3 Dental Anomalies

Mitra Saffar and Bert Braumann

In pre- and postnatal development, malformations can affect the dental ridges, the individual tooth buds or the alveolar processes. These malformations can have a genetic or environmental etiology.¹ The sites affected vary as does the degree of manifestation. Here, we will differentiate between morphological anomalies and tooth number anomalies.

Anomalies in tooth number are frequently observed and may be hypodontia (a deficit in the number of teeth) or hyperdontia (a surplus number of teeth). Anomalies in tooth number can affect both the primary and the secondary dentition. They especially occur at the end of ridges or in the area of fusion of the embryonic dental ridges. In hypodontia, there may be absence of individual teeth, hypodontia, and absence of entire groups of teeth, oligodontia. A complete absence of all teeth, anodontia, is rare and is generally associated with a syndrome.

Variations of tooth shape, including tooth size, are rarer and take different forms. We differentiate effects on the structural properties of the dentition from the effects on individual teeth or groups of teeth. Examples of the former are amelogenesis and dentinogenesis imperfecta. If individual teeth are dysplastic, the cause may be trauma or exogenous factors such as dental fluorosis.

The diagnosis of dental abnormalities is very important. Particularly in adolescent patients, early recognition of dental abnormalities contributes to the prevention of long-term adverse effects on dentition and occlusion and supports early therapeutic intervention.

Conventional diagnosis of dental abnormalities is done at the clinical examination and in radiological diagnostic procedures. The latter enables diagnosis of any malformations in teeth that have not yet erupted and can exclude dysplastic developments.

In contrast to conventional 2D radiological diagnosis, 3D imaging permits erupted teeth and all tooth buds to be located without superimpositions and their developmental stage evaluated without requiring additional imaging procedures. Potential eruption difficulties or obstructions can be recognized early.

If dental morphological anomalies are found, 3D diagnosis is used in assessing the tooth buds and their long-term prognosis.

3.1 Anomalies in Tooth Number

3.1.1 Hypodontia

Hypodontia is defined as the absence of single or multiple teeth of the same group of teeth. It can affect both the primary and the secondary dentition.

In the deciduous teeth, the upper lateral incisors or the lower mesial or lateral incisors can be absent. In the permanent dentition, absence of teeth occurs most frequently in the wisdom teeth

(approximately 25%). In decreasing frequency, it affects the lower second premolars (about 5%), the upper lateral incisors (about 3%), the upper second premolars and the lower mesial incisors.² In hypodontia, the existing teeth generally do not exhibit changes in size or shape.

Delayed mineralization, bud displacement or microdontia are considered microsymptoms of dental agenesis (Figure 3-1).³

Late eruption of teeth, inclusion or reinclusion of persistent lower second deciduous molars is frequently a sign of agenesis of the second premolars (Figure 3-2).

Oligodontia

Oligodontia is defined as agenesis of several teeth of different tooth groups. Oligodontia differs etiologically from hypodontia. The existing teeth exhibit clear changes in size and shape. Complete absence of the tooth buds, so-called anodontia, occurs very rarely (Figures 3-3 to 3-5).

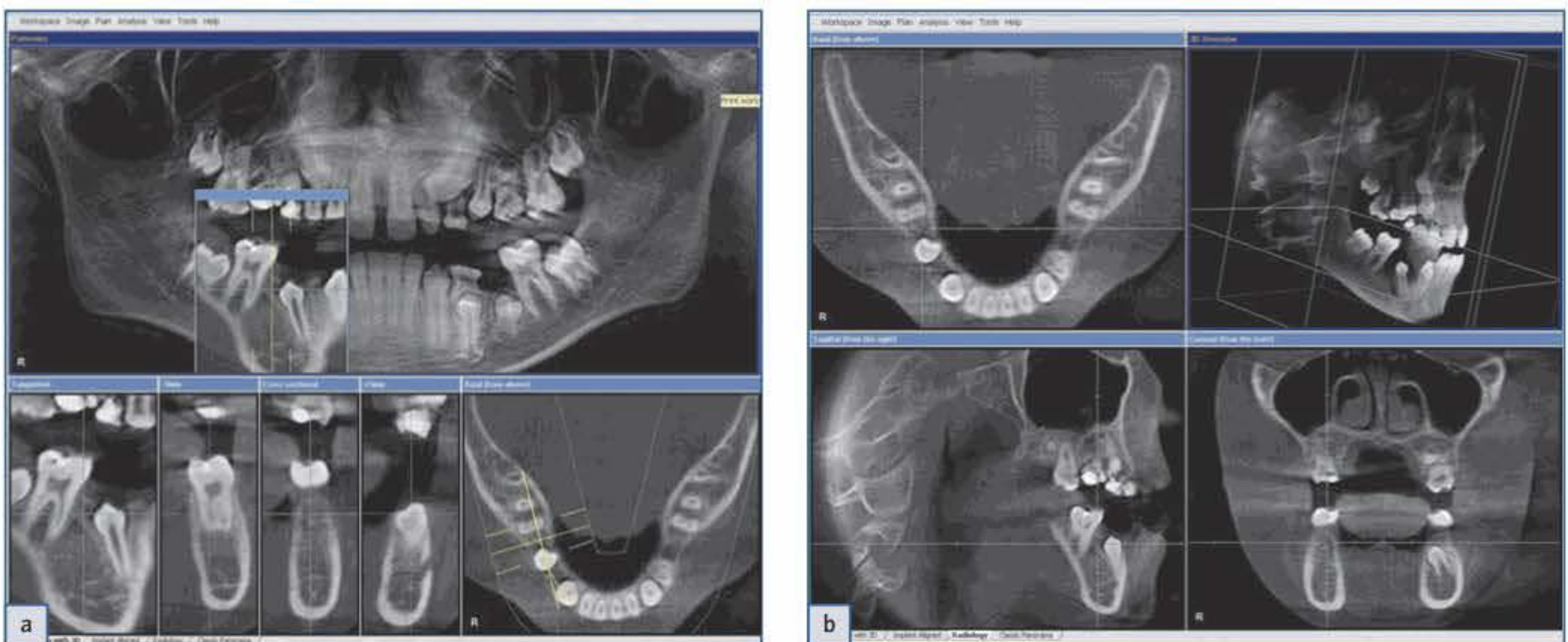


Fig 3-1 A 10-year-old girl with hereditary history and agenesis of teeth 15 and 45. (a) The cone-beam image demonstrates the agenesis of 15 and 45 as well as delayed mineralization of tooth germs 25 and 35. In addition, 13 and 23 are dislocated. (b) In the axial and transverse image slices for the same patient, a distal migration of the crown of tooth germ 44 can be seen following the loss of tooth 85.



Fig 3-2 A 15-year-old male following completed orthodontic treatment, with persistence of 85, agenesis of 45 and adequate space. The high-resolution view of 85 in the examination window permits a better assessment of the possibility of leaving 85 as a placeholder. While the mesial root is well preserved, the distal root exhibits idiopathic root resorption.



Fig 3-3 A 5-year-old boy with preoperated left-sided cleft lip and palate and deciduous dentition destroyed by caries. Hypoplasia of 12, 22, 15, 25, 17 and 27 with hereditary etiology.



Fig 3-4 An 18-year-old female following completed orthodontic treatment alio loco and prior to implantological treatment. Agenesis of 12, 13, 14, 15, 22, 23, 24, 25, 33, 31, 41, 43 and 44.



Fig 3-5 An 18-year-old male following completed orthodontic pretreatment lasting several years, alio loco in addition to agenesis of 14, 17, 18, 24, 27, 28, 38, 37, 34, 31, 41, 44, 47, 48; there is a congenital cranial asymmetry that necessitates bimaxillary corrective osteotomy.

3.1.2 Hyperdontia

Hyperdontia is defined as a surplus of one or several teeth. It occurs more rarely than hypodontia and is seen in 0.2 to 2% in the primary dentition and in 0.1 to 4% in the permanent dentition.⁴ Hyperdontia occurs preferentially in the fusion area and at the ends of the dental ridges. In the primary dentition, it is generally located in the region of the upper incisors, while in the permanent dentition, it is particularly found in the area of the maxillary anterior teeth and in the area of the mandibular premolars. Surplus teeth frequently exhibit malformations in the shape of the tooth (Figures 3-6 to 3-8).⁵



Fig 3-6 A 10-year-old boy with supernumerary tooth bud in the region of tooth 12. The transverse slice of the panoramic view shows the supernumerary 12, situated palatal and caudal to 13, with a shortened root. It differs from the regular 12, which can be identified further mesially rotated in the transverse slice. During orthodontal treatment, the supernumerary 12 was removed.

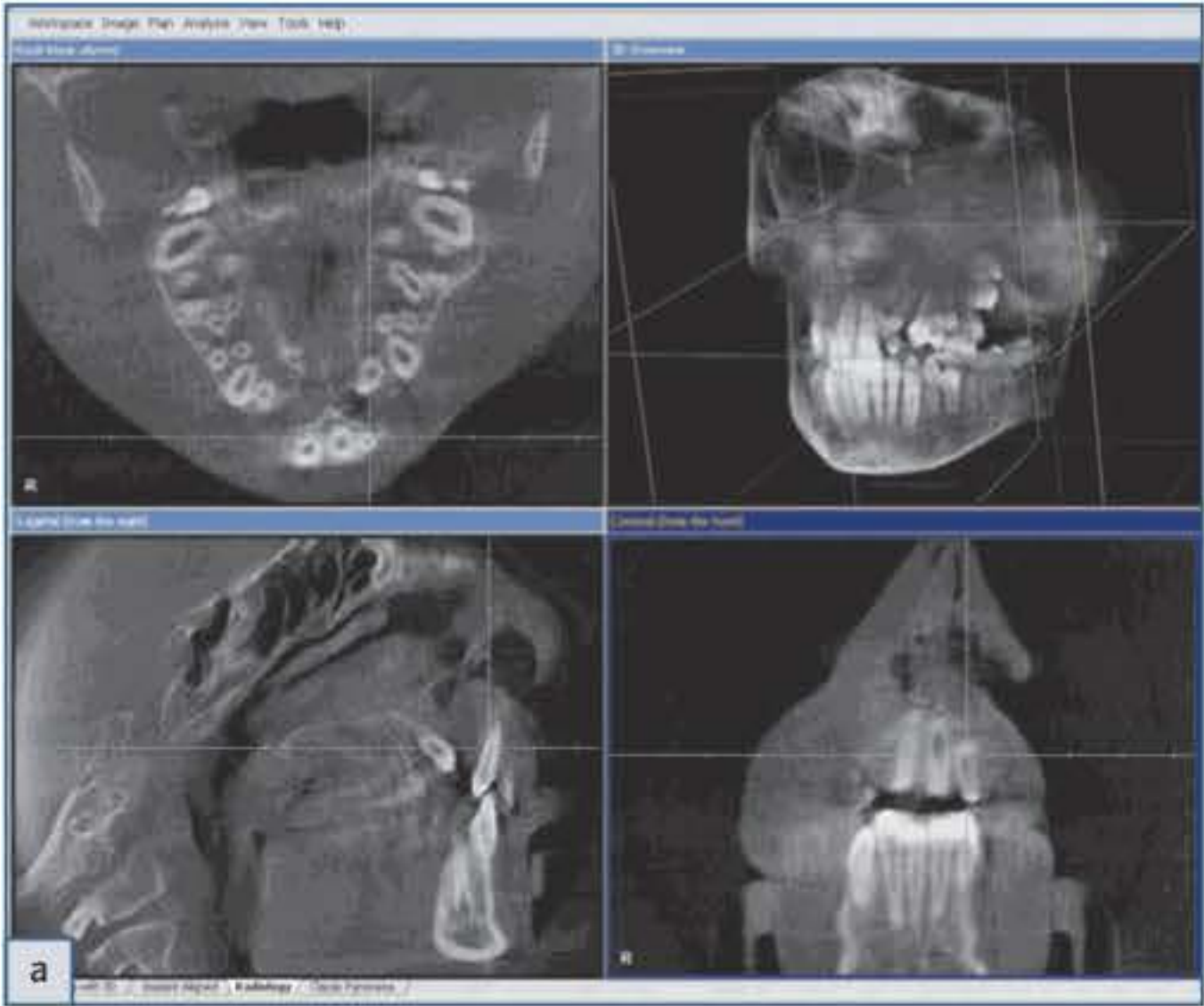


Fig 3-7 An 11-year-old boy with pre-operated unilateral cleft lip or palate and supernumerary tooth germ in the left anterior tooth region. (a) A 12 can be located both in the mesial and in the distal segment, both of which are in anterior cross-bite. (b) The 3D image permits an assessment of the developmental stage of the tooth germs and supports the therapeutic decision regarding the preservation and the feasibility of inclusion of the teeth.

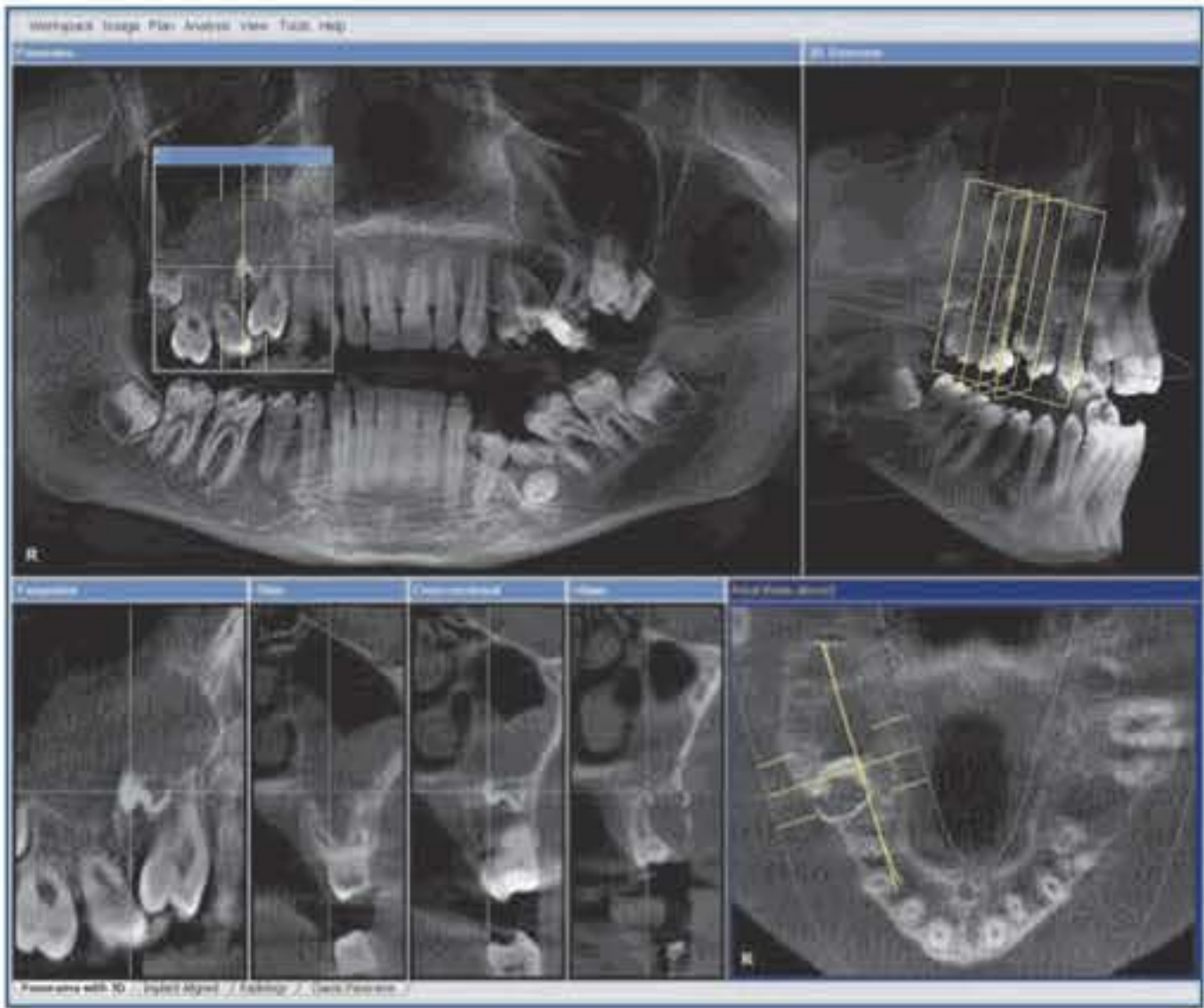


Fig 3-8 A 13-year-old boy with a supernumerary tooth in the region of 15 and tooth retentions in the regions of 25, 35 and 34. To plan the surgical removal of the teeth, they were located in transverse and tangential slices, and the position occupied by 15 relative to the maxillary sinus was determined. After removal of 26, which was destroyed by caries, 25 and 27, the horizontally dislocated 35 and the impacted 34 could be integrated.

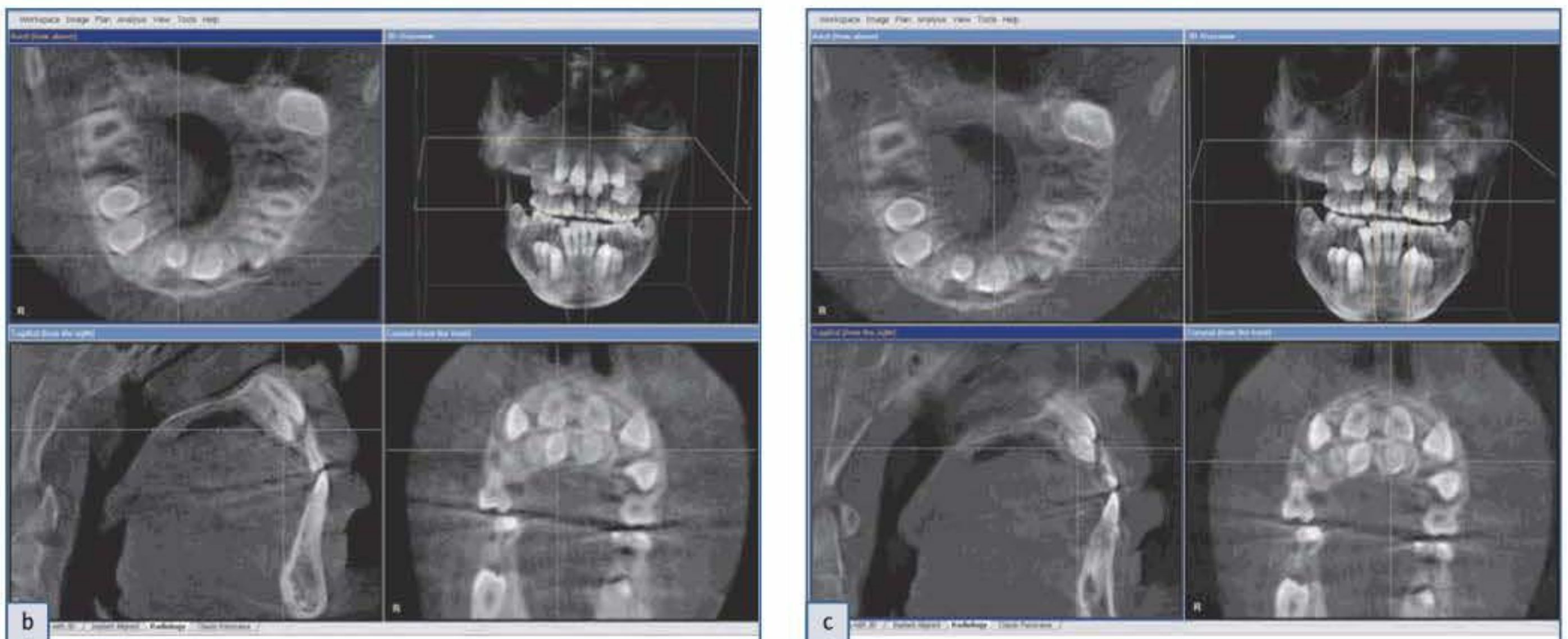


Fig 3-9 A 9-year-old boy with persistent deciduous teeth in the maxillary incisors. (a) Owing to the age-inappropriate clinical findings, a 3D image was taken. In the axial, sagittal and coronal slices, the presence of the bilateral supernumerary dysplastic tooth germs in the anterior maxilla was confirmed, whose palatal location prevented the eruption of the normally developing 11 and 21 and consequently caused their retention (b, c).

Mesiodens

Mesiodens is defined as a supernumerary tooth between the mesial upper incisors. Mesiodens are frequently conical and may be impacted. They can result in delayed eruption of the upper front teeth or in the formation of a mesial diastema.²

In contrast with 2D imaging, they can be very accurately located in 3D imaging. Their diagnosis is more difficult in the panoramic radiographic image due to the low slice thickness in the region of the anterior teeth, as they are located outside of the depicted slice.⁶ In addition, the 3D image allows precise evaluation of the location of the mesiodens relative to the nasal floor (Figures 3-9 and 3-10).



Fig 3-10 A 13-year-old boy in orthodontic treatment. The diffuse radiopacity between the upper mesial incisors justified the preparation of the 3D image. In the transverse slices, the 180 degree inverted mesiodens can be clearly identified, and its position to the two mesial incisors can be assessed in preparation for its surgical removal.

Paramolars

Paramolars are supernumerary, generally dysplastic, teeth occurring unilaterally or bilaterally in the premolar or molar region. The 3D image allows them to be located in the buccolingual direction. At the same time, their root development can be evaluated and compared for subsequent extraction decisions (Figure 3-11).

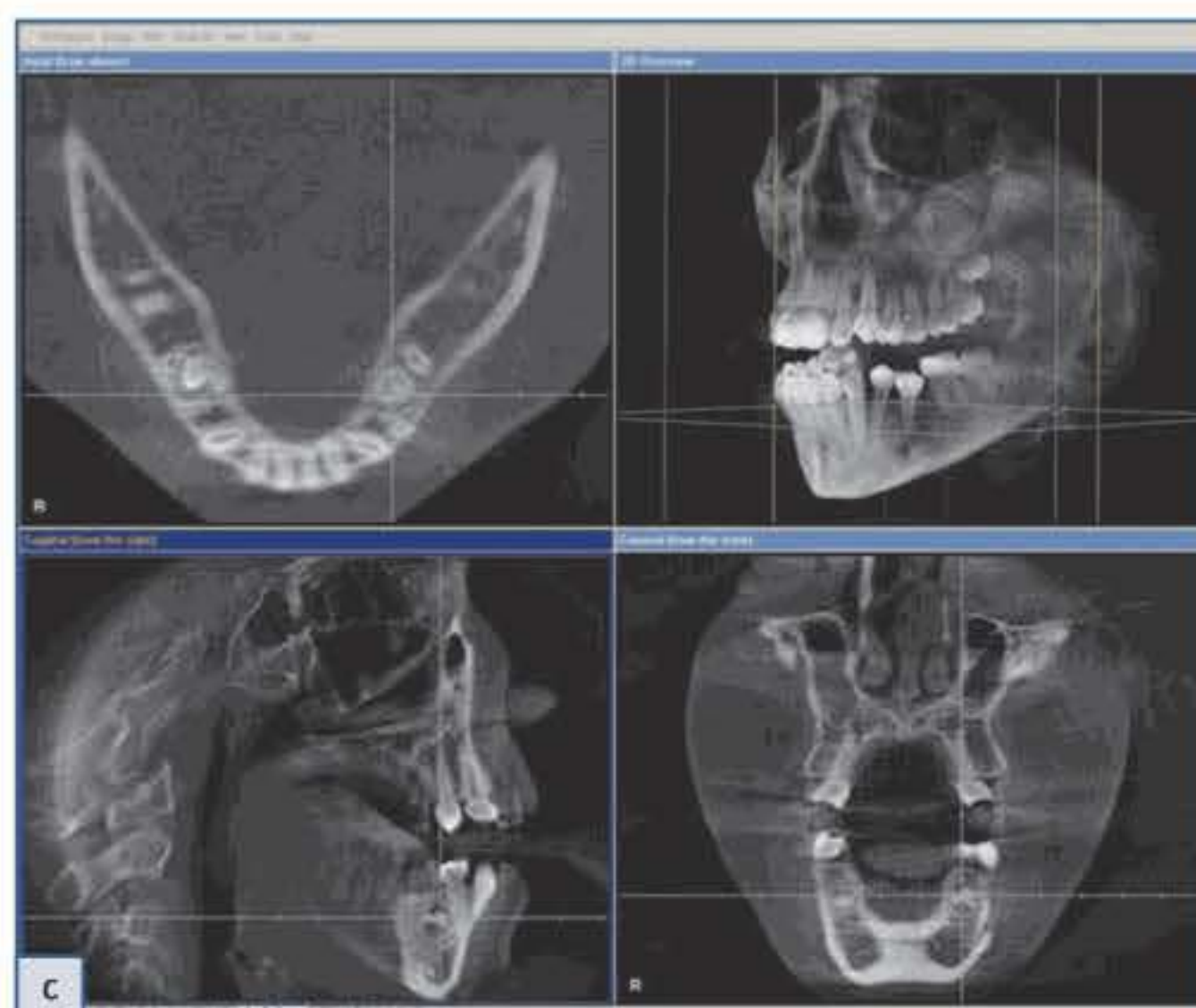


Fig 3-11 (a) A 13-year-old boy with bilateral supernumerary teeth in the region of the mandibular premolars. Only the view in the axial (b) and coronal (c) slices allowed complete localization of the two paramolars that were dislocated in the lingual cortex.

Distomolars

Distomolars are supernumerary, generally dysplastic, teeth occurring unilaterally or bilaterally at the posterior end of the primary dental ridges. Distomolars are more frequently seen in the maxilla than in the mandible. Because of pronounced posterior crowding, they generally remain impacted in the jaw (Figure 3-12).

Syndrome-associated hyperdontia

Hyperdontia can also be diagnosed in conjunction with cleidocranial dysostosis. Three-dimensional imaging supports the dentist's decision as to which teeth can be aligned orthodontically and which teeth must be extracted in order to create satisfactory occlusion (Figures 3-13 and 3-14).

In addition to syndromal pathologies, supernumerary teeth frequently occur in the region of the cleft margins in conjunction with cleft lip and palate (Section 13.1).

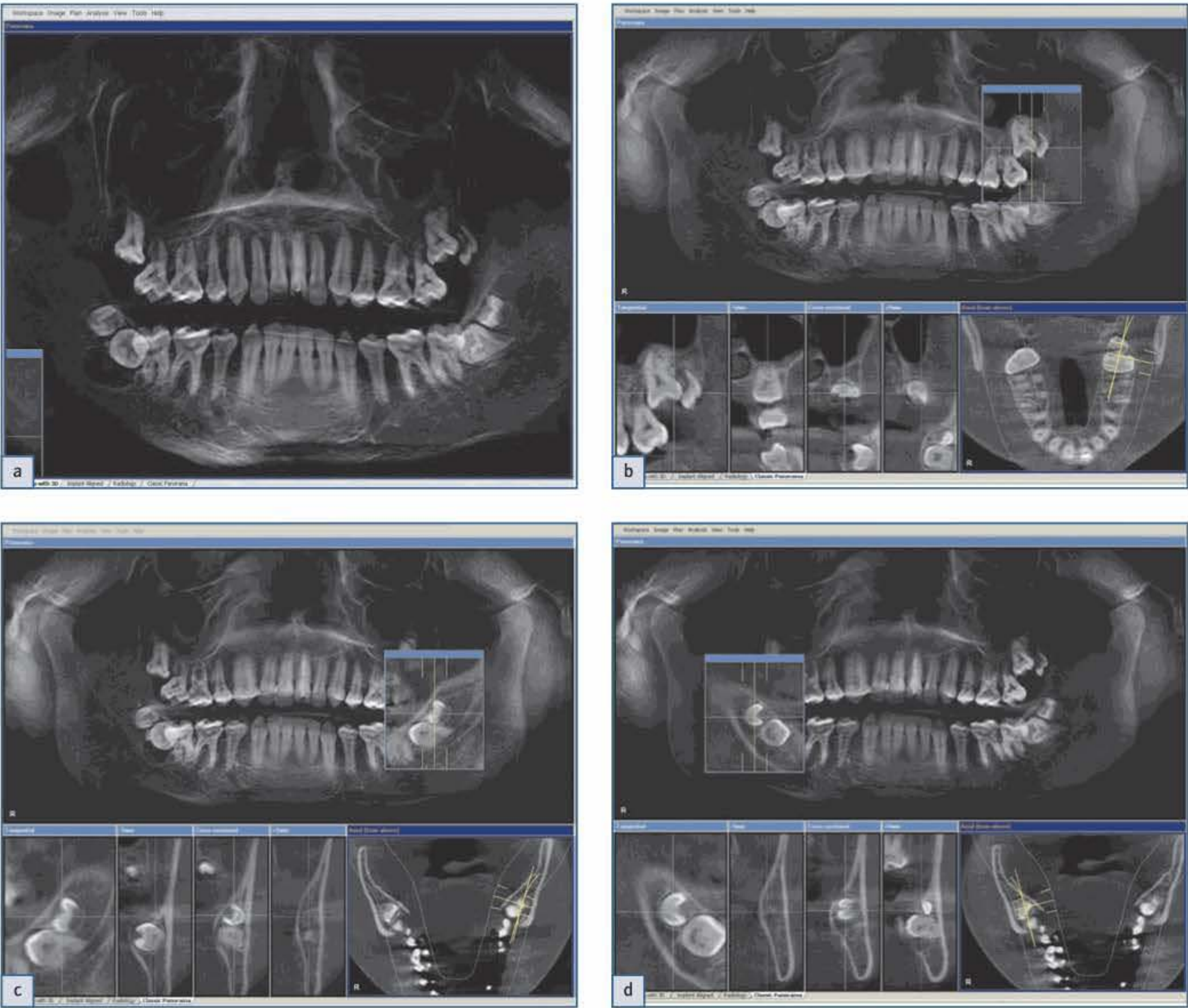


Fig 3-12 A 17-year-old male with unremarkable general medical history and anterior tooth trauma at 21. The views show the status after orthodontic treatment with extraction of 14, 24, 34 and 44 and attachment of a fixed retainer at the anterior mandible. There is a dislocation of 28, 38 and 48, and distomolars are present in the region of 29, 39 and 49.

Fig 3-13 A 17-year-old female with cleidocranial dysostosis. The views show the status after removal of multiple teeth in the maxilla and mandible. Using a fixed appliance, the dislocated 13, 23 and 33 are integrated into the dental arch. Along with the bilateral supernumerary teeth in the mandibular premolar region, displacement of 25, rotations of 35 and 45 and a double projection in the region of 37 and 38 can be identified.



Fig 3-14 A 14-year-old male with hyperdontia in cleidocranial dysostosis and bilateral supernumerary teeth in the mandibular premolar region, undergoing current orthodontic treatment.



3.2 Dental Morphological Anomalies

Single or multiple teeth can be too small (microdontia), too large (macrodontia) or malformed (dysplasia). Deviations from the normal dental morphology are not considered pathological in all cases. Changes in dental morphology can occur both unilaterally and bilaterally. If single teeth are affected, it is considered a pathological alteration, while bilateral, symmetrical alterations are viewed as physiological.

In erupted teeth, radiologically diagnosed abnormalities of dental morphology must be compared with the clinical findings.

3.2.1 Microdontia

Microdontic teeth occur as a diminutive form of normal teeth or as so-called peg teeth in all incremental sizes, particularly in the permanent dentition. Microdontia can be local or generalized.⁴ The maxillary lateral incisors and the third molars are frequently affected. This is particularly clinically relevant when, in addition to an esthetic deficit, there are discrepancies in tooth width: that is, inconsistencies between the mesiodistal tooth width of a group of corresponding teeth in the maxilla and the mandible. Patients with cleft lip and palate are particularly affected (Figure 3-15).

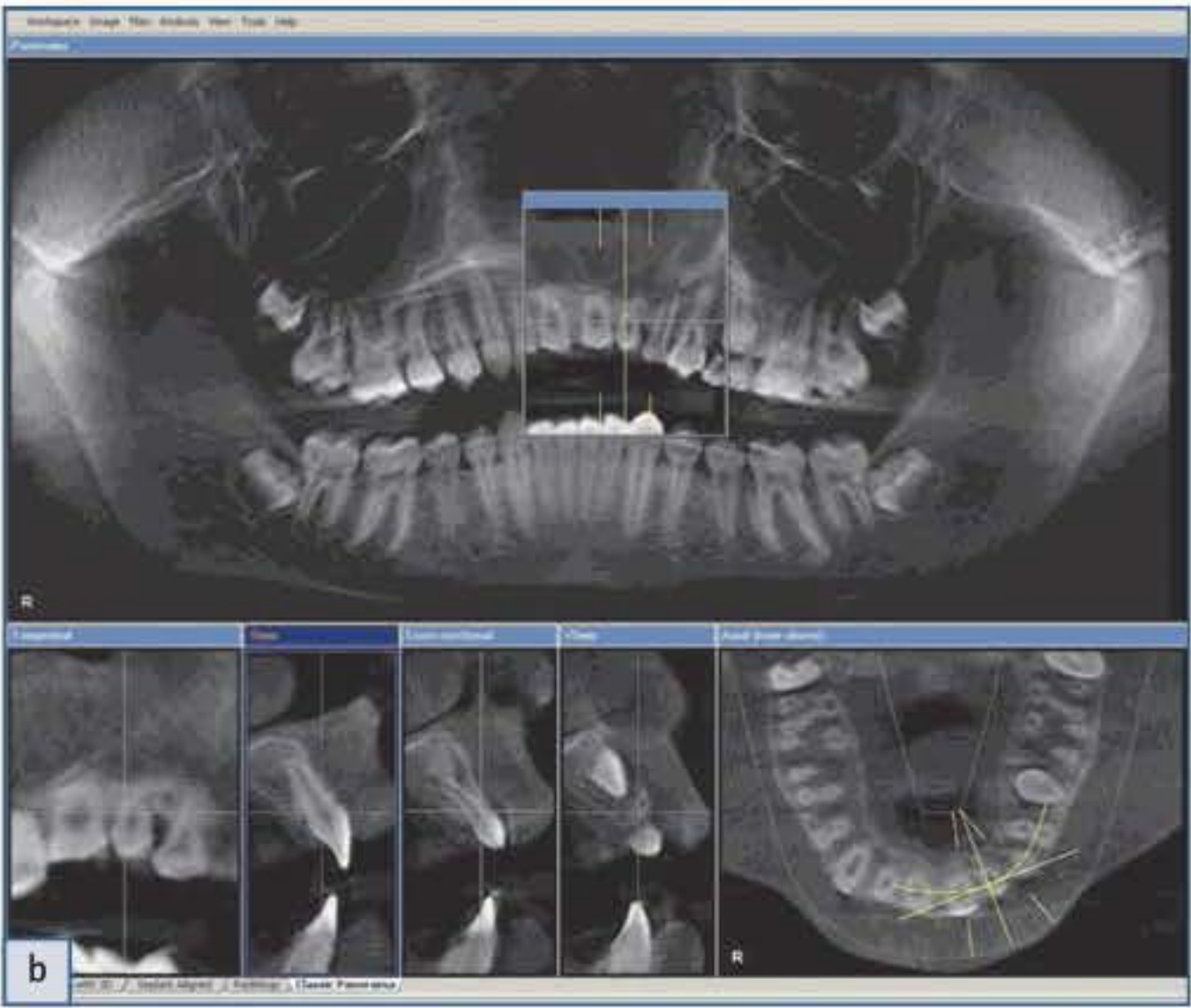


Fig 3-15 A 14-year-old boy with microdontia of 22 and persistence of 63 with displacement of 23. The root of 22 is palatinally curved owing to the displaced neighboring 23. This offset of the root can be very easily identified in the transverse slices of the panoramic view (b).



Fig 3-16 A 14-year-old girl with the formation of twin teeth in the region of the first mandibular left premolar. Geminations in the region of the mandibular premolars can occur in many variations. As in this case, they commonly have two pronounced pulp horns. The connection of the two pulp horns (recognizable in the axial and tangential slices) vitally contributed to the fact that a hemisection of the tooth was not an option with the existing spatial deficit in the dental arch.

3.2.2 Macrodonia

Macrodonia consists of one or several oversized teeth. The mesial maxillary incisors are particularly affected. A special form of macrodonia is the formation of twin teeth, which is also called gemination. This is defined as the incomplete fission of the tooth germ (schizodontia) or fusion of the tooth germ (synodontia).⁴ Only two adjacent, still unmineralized, tooth germs can fuse with each other. The fusion can occur in the enamel, the dentin or the cement (Figure 3-16).

3.2.3 Root Dysplasia

Abnormalities in dental morphology that are limited to the region of the tooth root are called root dysplasias. Evaluation of the roots of teeth is important, especially in endodontic and orthodontic treatment planning. Deviations in morphology and length are only two examples of the criteria that must be taken into consideration.

Dilaceration

Dilaceration (the development of a collum angle) is a special type of root dysplasia. It is an anomaly in tooth morphology that is generally caused by trauma and in which the root is continuously contorted to varying degrees (Figures 3-17 and 3-18).¹

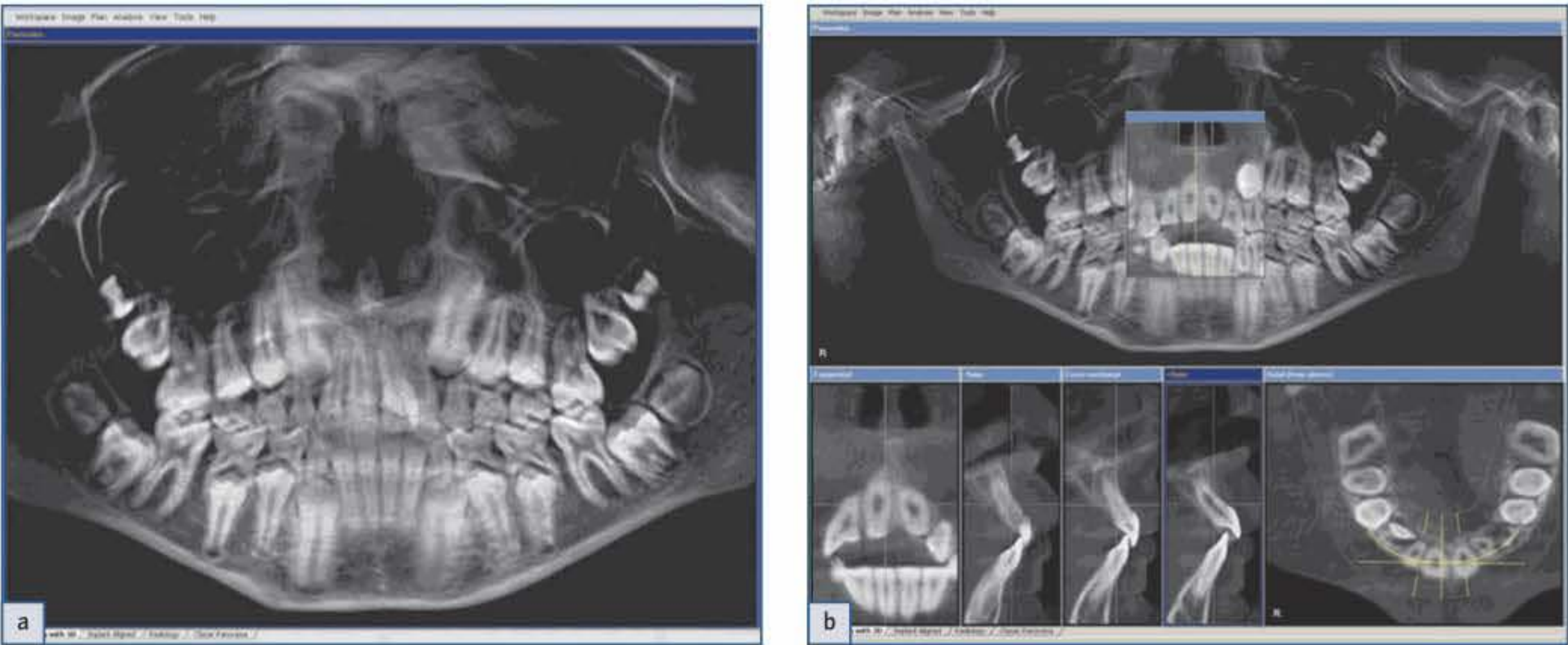


Fig 3-17 (a) A 10-year-old girl with unremarkable findings at 21 in the panoramic view. (b) A more detailed inspection of 21 in the transverse slices revealed an offset of the 21 root anteriorly. The cause was trauma to the anterior teeth in the deciduous dentition, which was indicated in the history.

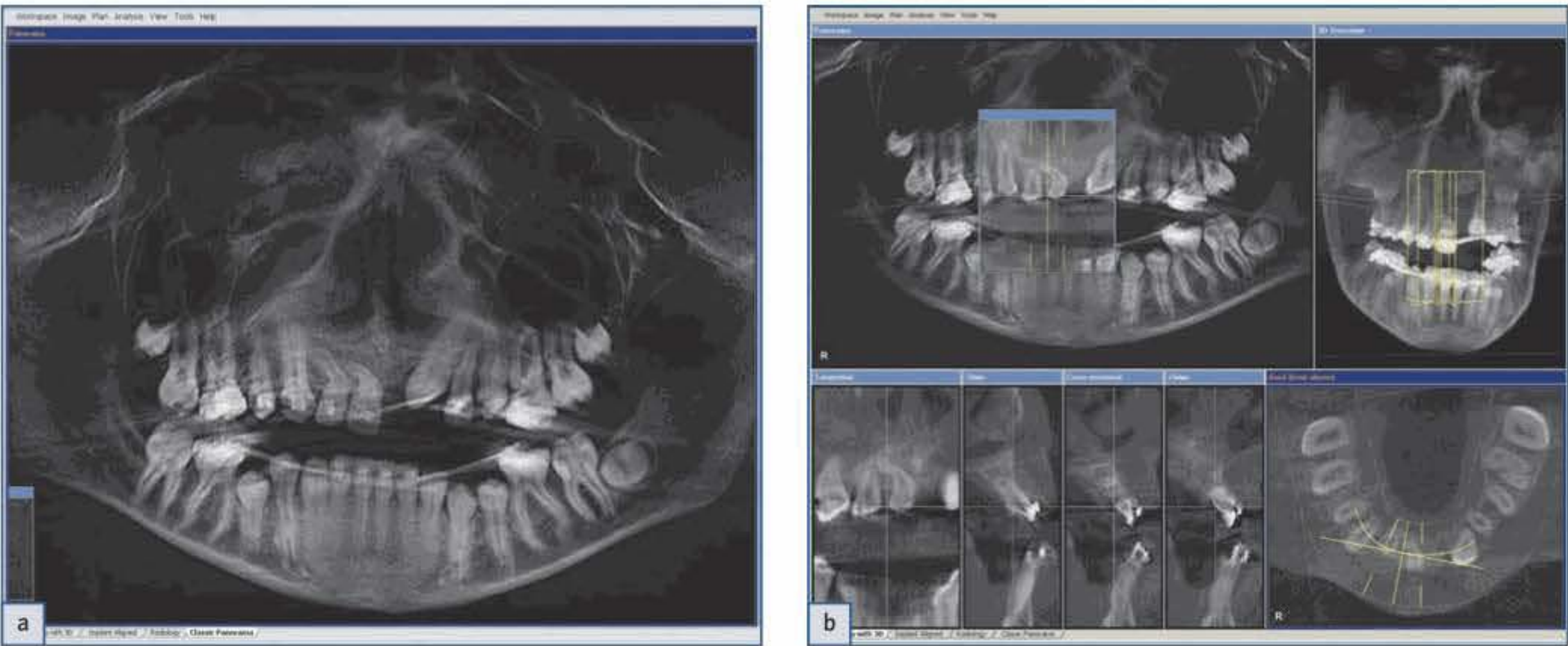


Fig 3-18 A 14-year-old girl with dilacerations of 11 and 12 of unclear etiology. The views show the status after extraction of 15, 25 and 21 and transpositioning of 12 and 13 in current orthodontic treatment. The double-truncated root of 11 can be seen in the transverse slices.

3.2.4 Root Resorption

Root resorption is found in both the deciduous and the permanent dentition. Physiological root resorption, such as in deciduous teeth at the time of eruption of the permanent teeth, is differentiated from pathological root resorption.

There are unexplained idiopathic root resorptions and iatrogenic root resorptions subsequent to orthodontic procedures or trauma. Gracile short roots, particularly in the anterior maxilla, indicate idiopathic resorption.¹⁻⁵ Depending on the severity and extent of resorption, it is either reversible or irreversible. Root resorptions frequently run a painless course.

As well as locating the root resorption, 3D imaging can evaluate the extent of the length loss (Figures 3-19 to 3-21).



Fig 3-19 A 16-year-old female following orthodontic treatment with extraction of four premolars. The transverse slices show the pronounced resorption in the anterior region of the maxilla and the mandible, with protrusion of the mandibular anterior dentition.



Fig 3-20 A 19-year-old male following orthodontic pretreatment with integration of a displaced 23. (a) The pronounced iatrogenic root resorptions in the region of the maxillary anterior dentition are the result of a pronounced protrusion of the front teeth. (b) In the axial slice, the cortical position of the tooth root of 23 and the pronounced palatal position of the root of 22 with little bone cover are visible.



Fig 3-21 A 19-year-old male with localized idiopathic root resorption at tooth 16 and agenesis and growth disorders in the left maxilla of unclear etiology.

3.3 Summary

Most abnormalities in tooth number and in tooth morphology justify the use of radiological images in the dental and jaw region. The radiological findings should always be compared with the clinical findings. The examiner's task consists of correctly assessing the information that is obtained in the images and initiating the necessary therapeutic procedures. The 3D image supplies additional information complementing conventional views and allows more accurate treatment planning so that the dentist can institute appropriate therapeutic procedures without additional imaging procedures.

3.4 References

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4 Impacted Teeth

Jörg Neugebauer, Mitra Saffar and Rusbeh Shirani

The surgical removal of retained or impacted teeth is one of the most common procedures in dentoalveolar surgery.¹ The primary cause of eruption disturbance is a lack of space. The third molars, which erupt last, are affected most frequently.² Depending on the horizontal growth of the jaw, the available space may be inadequate for the molars erupting last in the dental arch, resulting in impacted and/or ectopic wisdom teeth in the region of the mandibular angle. Apart from the wisdom teeth, the maxillary cuspids exhibit the highest incidence of eruption disturbances. These disturbances are usually caused by an early loss of the deciduous teeth, with mesialization of the premolars erupting before the cuspids. In addition to genetic factors, exogenous influences also determine the eruption of the permanent teeth, for example in impaction after trauma, apical periodontal pathologies and cyst formation.³ In all eruption disturbances, intimate anatomical relationships to the normal structures exist and so accurate diagnosis is helpful in preventing secondary injury when teeth persist in the abnormal physiological position.⁴ Dimensionally true diagnostics reduce the risk of complications during surgical removal, involving the surrounding anatomical structures such as the inferior alveolar nerve, the adjacent teeth, the maxillary sinus floor and the nasal floor.⁵ When planning the surgical procedure, detailed diagnostics facilitate a conservative surgical approach, particularly in the adolescent patient, so that minor soft tissue preparation and a precisely described osteotomy can be performed. Particularly in synodontia or dental malformations with associated impaction, preoperative diagnostics allow an estimation of the tooth's preservability and the planning of further therapeutic procedures.^{2,6}

4.1 Ectopic and Impacted Wisdom Teeth

In the wisdom teeth, space limitations often cause eruption disturbances, with symptoms ranging from severe pain to recurrent inflammatory reactions in the context of pericoronitis. In addition to the determination of the anatomical position of the tooth, the 3D image serves in the evaluation of crown and root structure and of root growth.⁵ The 3D image is particularly useful in evaluating potential damage to adjacent structures. From a surgical point of view, ectopic or impacted wisdom teeth are preferably removed after most root growth has occurred, thus ensuring better positional stability of the tooth in the surgical field than can be achieved with germectomy. The risk of nerve damage increases significantly with age, with 25 years being considered as the critical age. Especially where the root is close to the nerve canal, 3D diagnostics provide greater diagnostic reliability than the combination of panoramic radiography and cranial PA survey imaging (occipitofrontal beam path, 15 degrees inclination with open mouth) (Figures 4-1 to 4-8).⁷ Cysts may form with advanced age or pronounced displacement; diagnostics for this are described in Chapter 5.



Fig 4-1 An 18-year-old female with eruption disturbance of wisdom teeth 18, 28, 38 and 48 and follicular cyst at tooth 48. Owing to the absence of tooth 37, orthodontic guidance of tooth 38 to position 37 was planned. A pericoronal lucency is seen at tooth 48, which continues into a clearly discernible periodontal space. The root growth of the wisdom teeth was not yet complete.

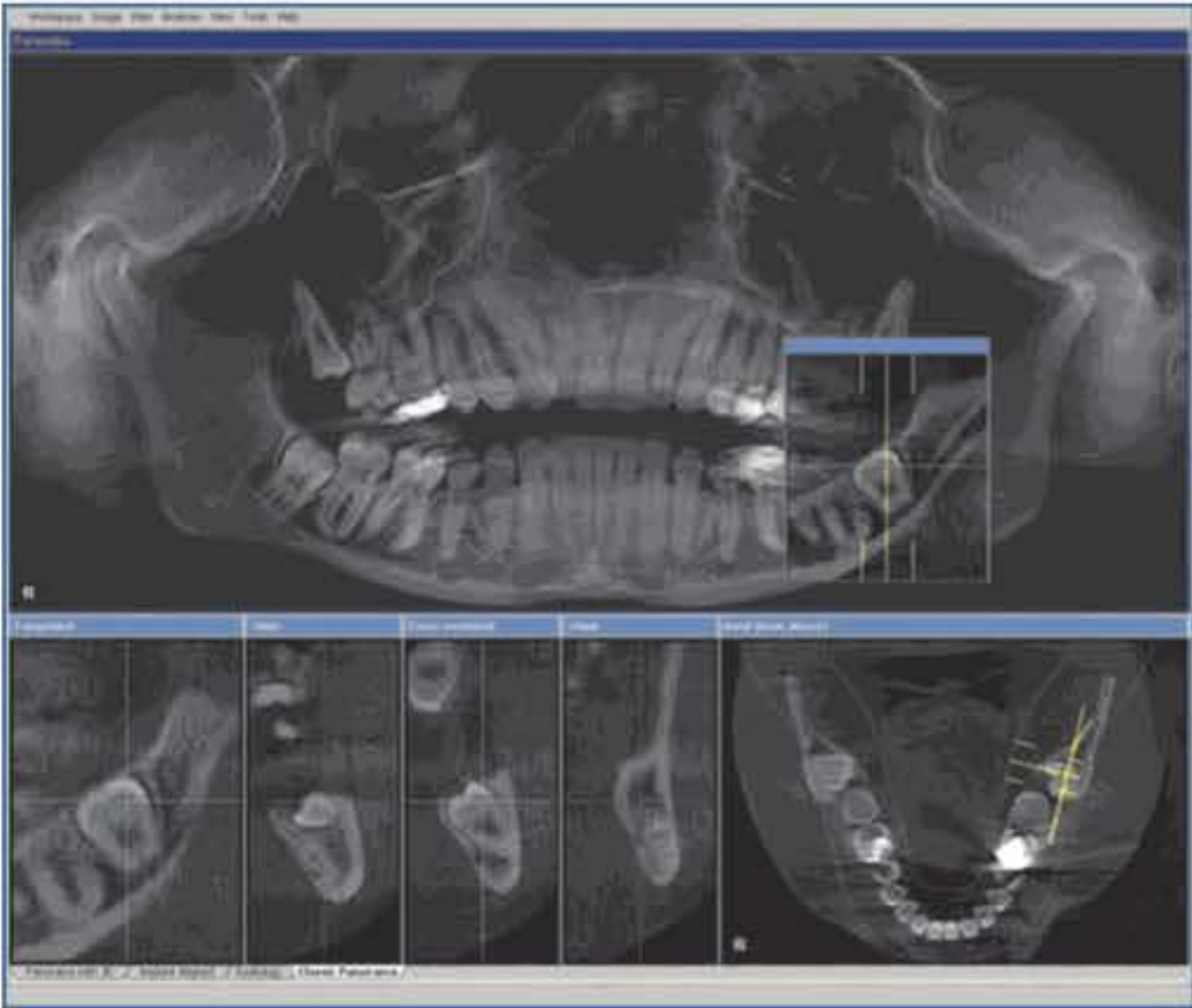
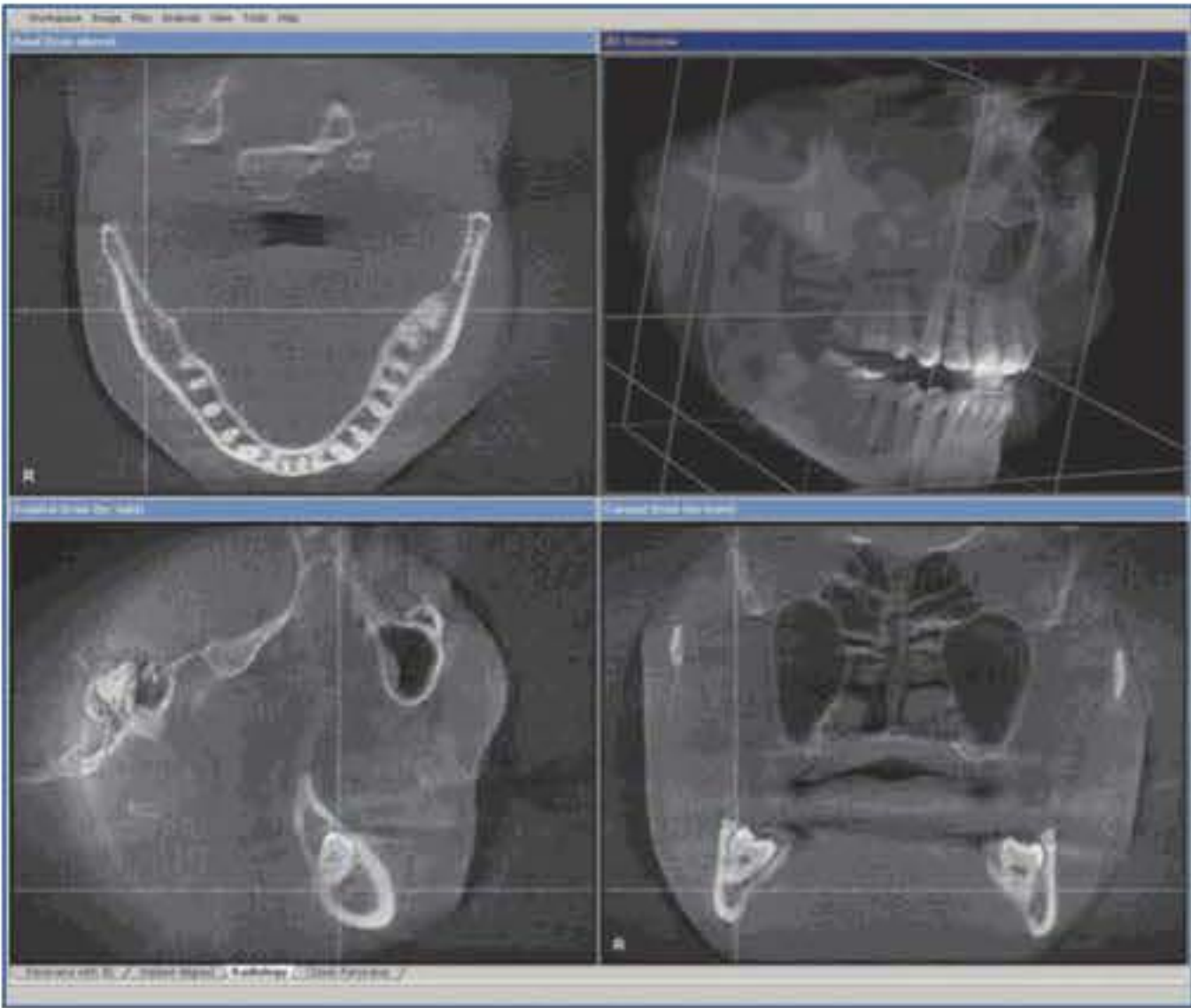


Fig 4-2 A 26-year-old female with vertically displaced teeth 18 to 48. The inferior alveolar nerve can be seen lingual to the root. The periodontal space now only exhibits a minor expansion. In the root area, the vestibular cortical structure of the mandible exhibits no differentiation relative to the root dentin.



Fig 4-3 A 35-year-old female with eruption disturbances of teeth 38 and 48. A pericoronal lucency at tooth 48 indicates a follicular cyst. Osteolysis in the region of the ascending ramus of tooth 38 gave clinical symptoms of pericoronitis. The coronal slice confirmed the lingual position of the inferior alveolar nerve at tooth 48, which is shown in the examination window.



As a rule, impaction of wisdom teeth is less pronounced in the maxilla than in the mandible. To aid in the prevention of an oroantral fistula (OAF), 3D diagnostics can provide accurate information regarding the position and characteristics of the roots and of the osseous boundary to the maxillary sinus.

Fig 4-4 A 47-year-old male with mesioangularly displaced 38 and eruption disturbance at 48. Only minor osteolysis can now be seen distal to the crown of tooth 38. The pericoronal lucency at tooth 48 has partially radiopaque structures. Cortical bone structures and tooth root can now only be differentiated to a limited degree.

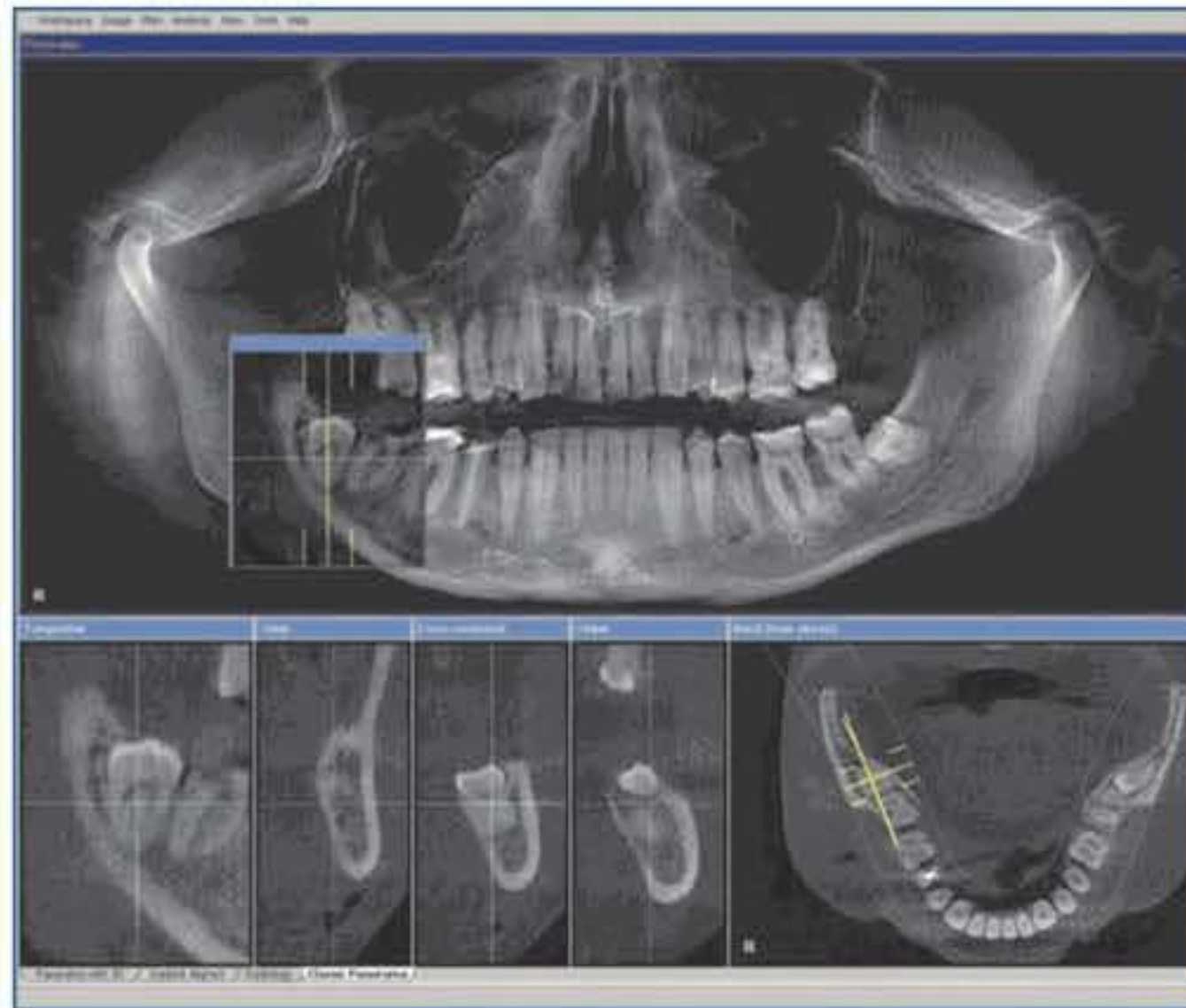


Fig 4-5 A 55-year-old male with impacted 38 and 48. (a) In the panoramic view, the transverse displacement of 38 looks as it does in a classical orthopantomograph image. The pericoronal lucency can only be discerned mesially at tooth 48. The transition between root and bone is indiscernible, particularly at the level of the nerve canal running vestibularly. (b) In horizontally distally displaced tooth 38, the lingual root path and the vestibular course of the inferior alveolar nerve relative to the root can be seen. The round projection seen in the panoramic representation is a physiological tooth shape in the slice image.

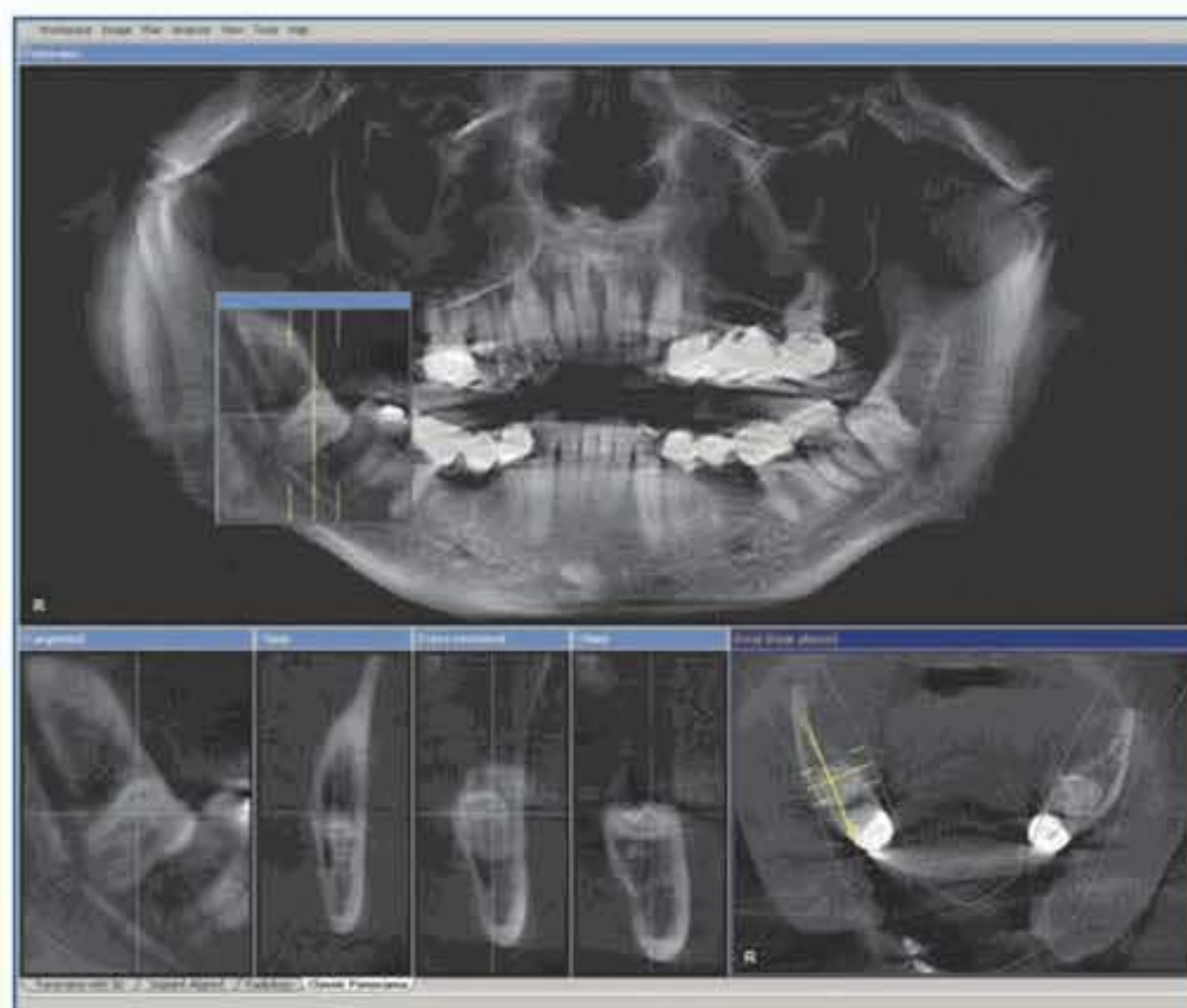


Fig 4-6 A 67-year-old male patient with vertically displaced 38 and 48. The radiopaque structures of the teeth and the bone structure are completely merged together. The nerve canal running lingually to the root attaches directly to the root surface in the absence of any visible bone structures.



Fig 4-7 A 75-year-old clinically edentulous patient with impacted 28 and 38. The inclinable examination window reveals the ectopic course of the inferior alveolar nerve around the root tip of tooth 38. The radicular dentin cannot be differentiated from the surrounding cortical bone. The image was prepared at a time of increasing pain in the left jaw region caused by a pressure point under the prosthesis in the area of tooth 38. The distension around the crown was classified as a follicular cyst.

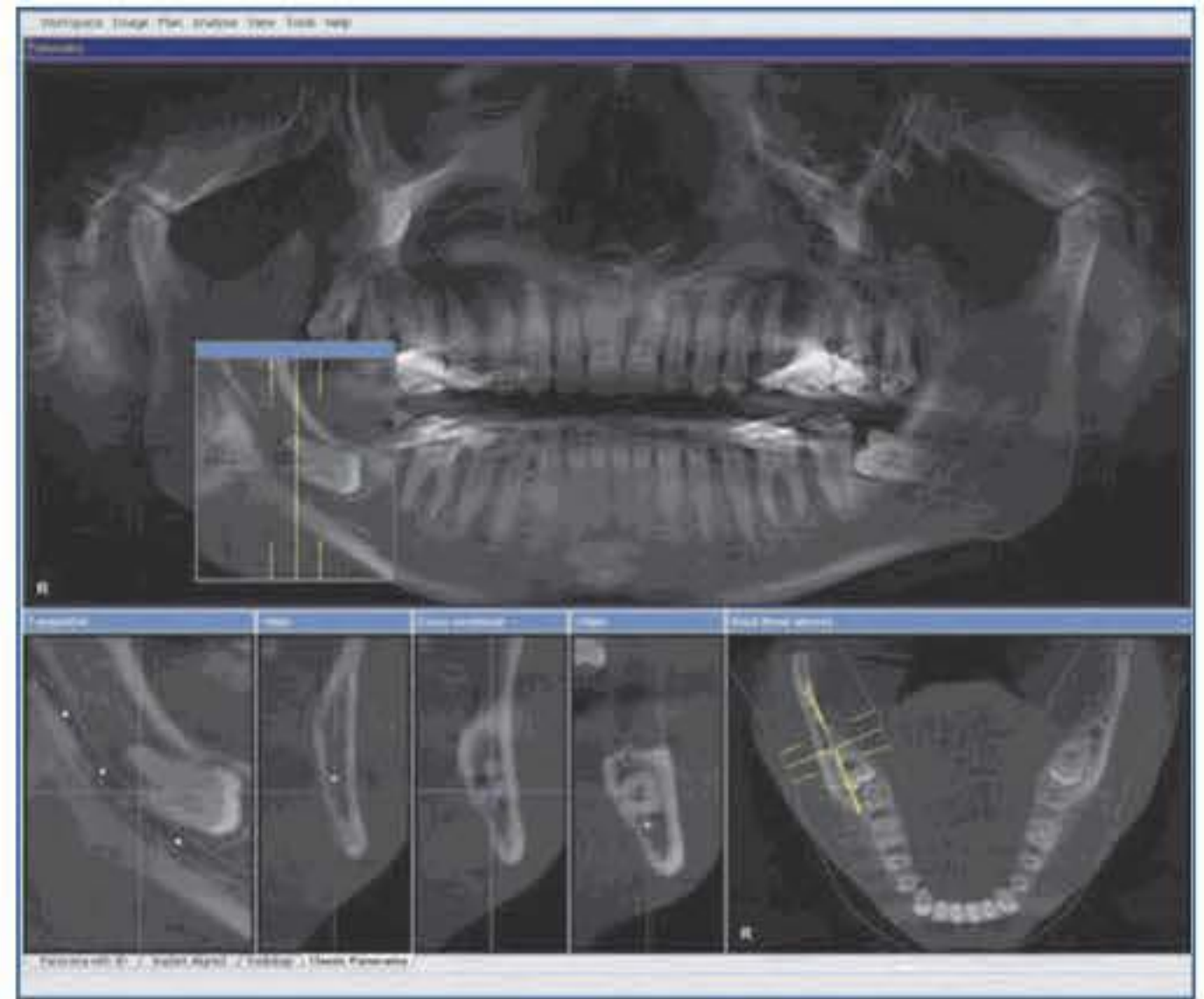


Fig 4-8 Improved representation of the nerve using colored marking of the bony channel: the distinctive nerve course with bracketing of the inferior alveolar nerve by the root tips of tooth 48 can be seen. Despite the difficult anatomical relationship between the mesial root and the nerve canal, osteotomy is indicated because of increasing pericoronal osteolysis in the presence of a follicular cyst. The accurate positional determination facilitated root separation and atraumatic osteotomy.



Fig 4-9 Incidental finding of a clinically asymptomatic vertically displaced 28. The slices revealed a maxillary sinus opacity, indicating a follicular cyst. The tooth was relatively loosely anchored by curved root, so a simple luxation was presumed. Access for the osteotomy was supported by computer-assisted surgery.

In the very rare cases of extreme displacement of wisdom teeth in the maxilla, 3D diagnostics permit accurate positional determination and the assessment of cystic changes, thus also determining whether extraction is indicated (Figure 4-9). Such teeth can be easily located and tissue removed conservatively with computer-assisted surgery (Chapter 15).

4.2 Other Ectopic Teeth

With the exception of the wisdom teeth, the diagnosis of impacted or ectopic teeth is generally incidental because they are often clinically asymptomatic and are rarely accompanied by other pathological processes.⁸ Excluding the wisdom teeth, the maxillary and mandibular second molars and the maxillary cuspids are most frequently displaced.⁹ If the clinical examination finds delayed eruption, dental migration or an alteration in the bony structures such as a prominence, an x-ray image should be taken.

4.2.1 Ectopic Incisors

Ectopic incisors are associated with supernumerary tooth buds in the anterior maxillary region and can also result from trauma to the deciduous dentition. Three-dimensional imaging allows the exact localization of the tooth and the identification of its root length and root form. Ectopic frontal teeth frequently exhibit a bend in the root (i.e. a dilaceration) that can complicate the alignment of the tooth (Figures 4-10 to 4-12).⁸

4.2.2 Ectopic Maxillary Cuspids

Ectopic cuspids occur in 1 to 3% of the population, making them less common than ectopic wisdom teeth.¹⁰ Palatal displacement is 2.5 to 5 times more common than buccal displacement. A

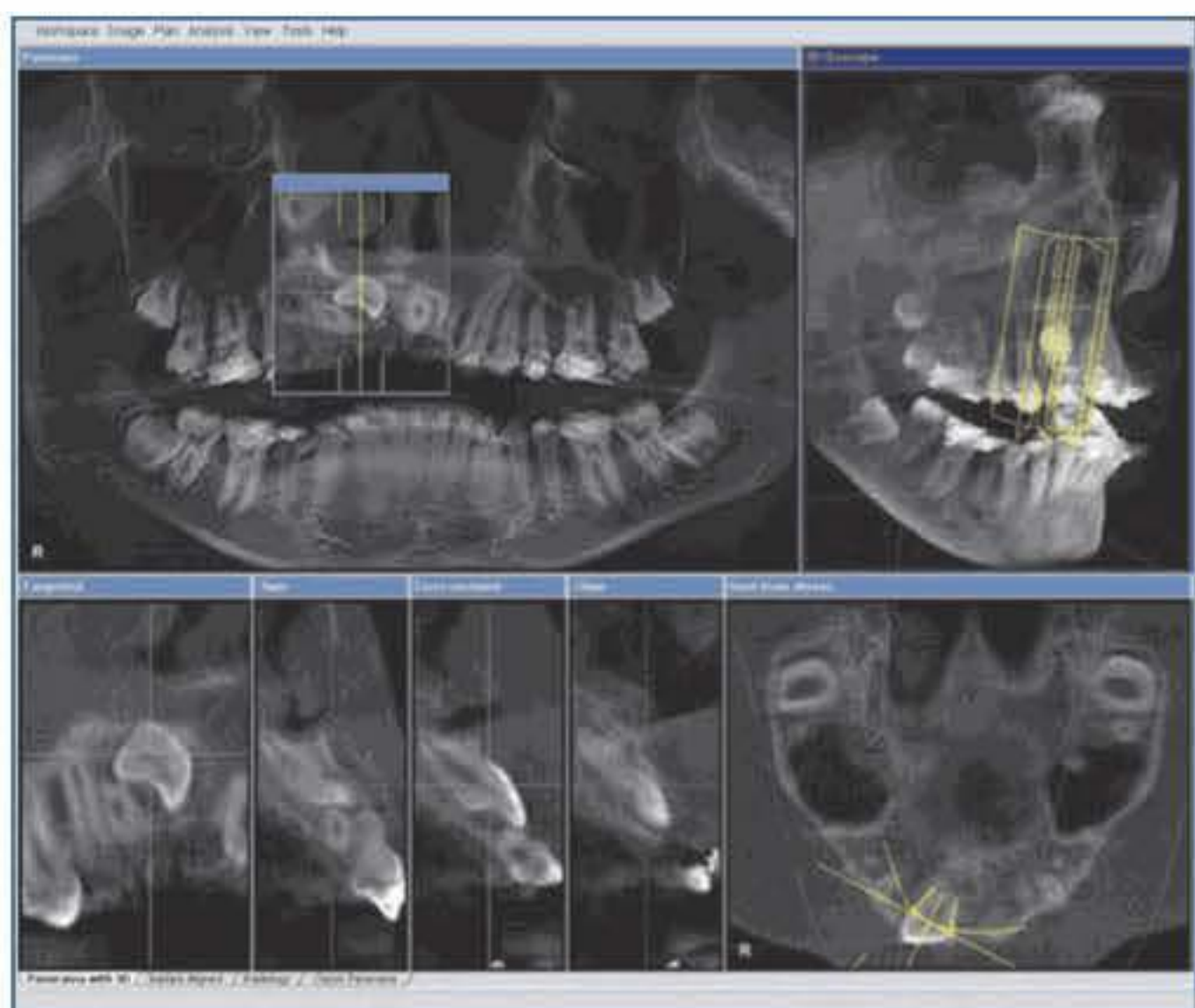


Fig 4-10 A 15-year-old female with a very late diagnosis of vertical displacement of tooth 11 with a persistent tooth 51 and mesial migration of tooth 12. The transverse slices visualize the rotation of 11, its shortened root and its buccal position relative to the adjacent tooth 12, which shows resorption. This facilitates selection of the best orthodontic treatment approach to avoid damaging the adjacent tooth 12.



Fig 4-11 A 10-year-old boy with extreme horizontal displacement of tooth 21 of unclear etiology. The questionable morphology and suitability for alignment based on conventional imaging is not confirmed on the 3D image, which supports orthodontic alignment based on the available space.

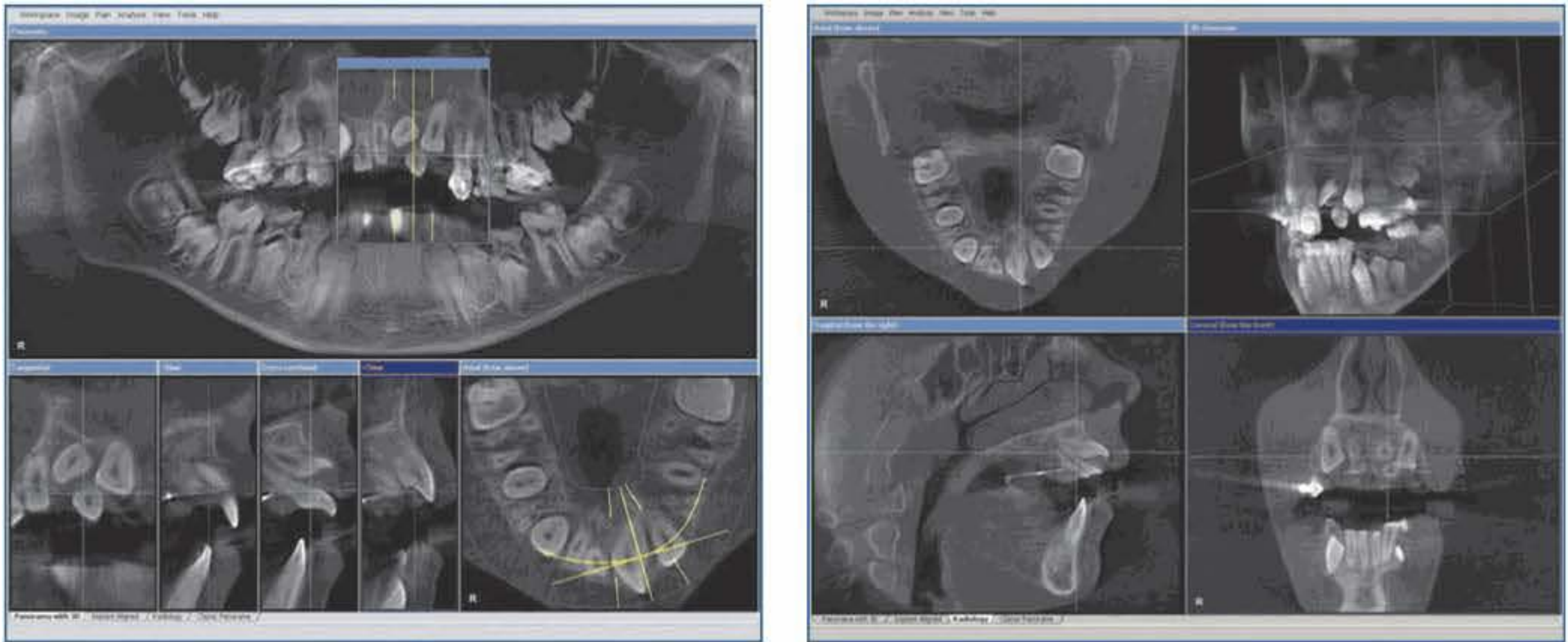


Fig 4-12 An 11-year-old boy with displacement of tooth 21 cranial to tooth 22 of unclear etiology. The immediate proximity of teeth 21 and 22 can be seen in the transverse slices. As tooth 25 had failed to develop, the adjacent teeth 24 and 23 could be moved distally to align teeth 21 and 22 without damaging their roots.

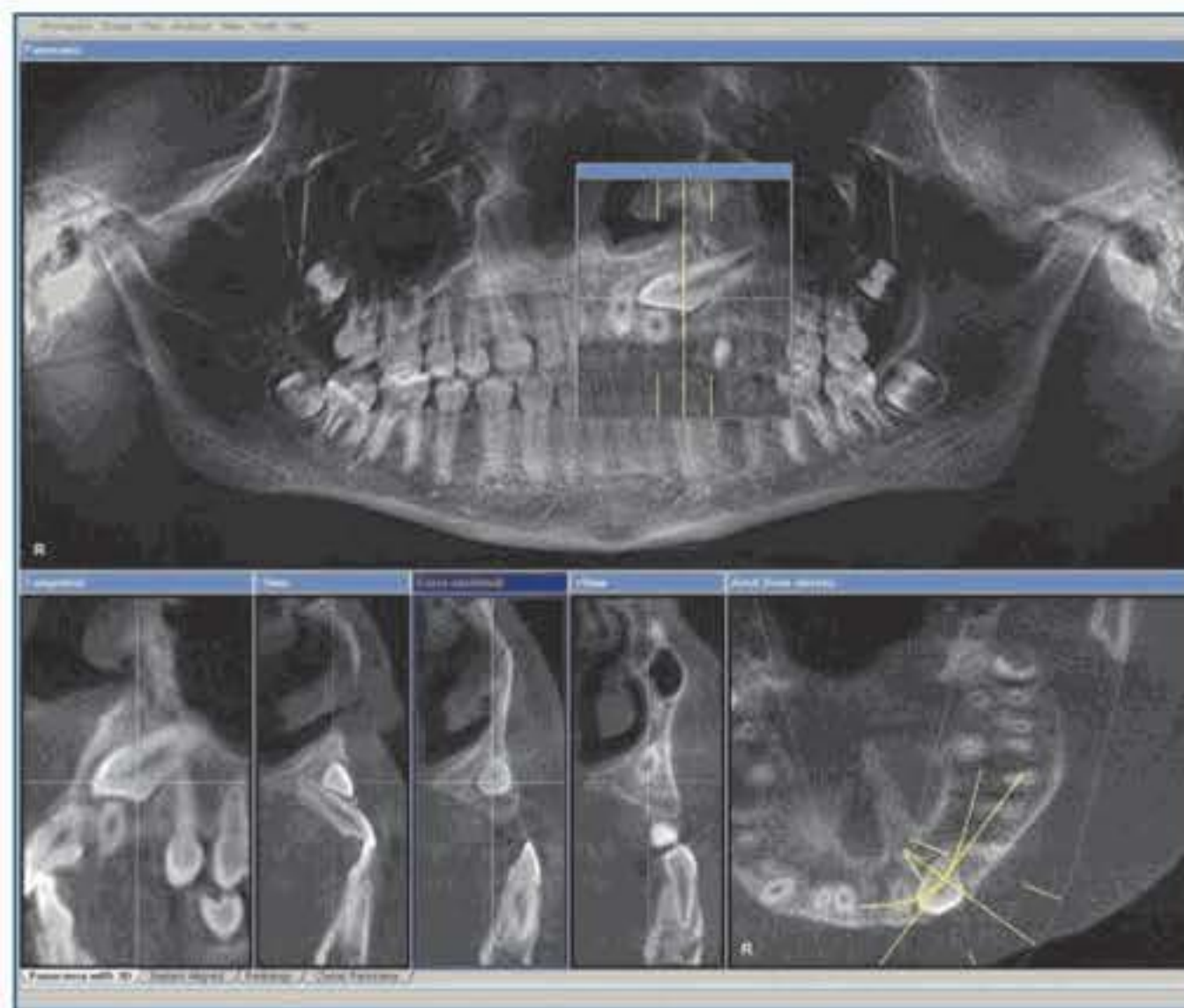


Fig 4-13 A 12-year-old girl with the following clinical finding: all permanent teeth have erupted with the exception of the left permanent cuspid, which is buccally displaced and will be orthodontically corrected. The transverse slices show the immediate proximity of teeth 23 and 22 and the absence of root resorption at tooth 22.

close topographic relationship with the adjacent teeth often exists, and the root may deviate from the longitudinal axis. Radiological examination of these clinically invisible teeth provides information on their location and morphology and on adjacent structures.¹¹ This includes their positioning and angulation in the dental arch, their developmental stage, the shape and length of the root, the size of the follicle and possible resorptions of adjacent teeth.

Two-dimensional images are of limited use. Three-dimensional imaging of ectopic cuspids permits their differentiated examination and serves as a valuable diagnostic tool. In contrast to conventional 2D imaging, teeth can be located more accurately using 3D imaging. In addition, the periodontal gap can be assessed for orthodontic correction procedures and any existing damage to adjacent structures can be evaluated (Figures 4-13 to 4-15).

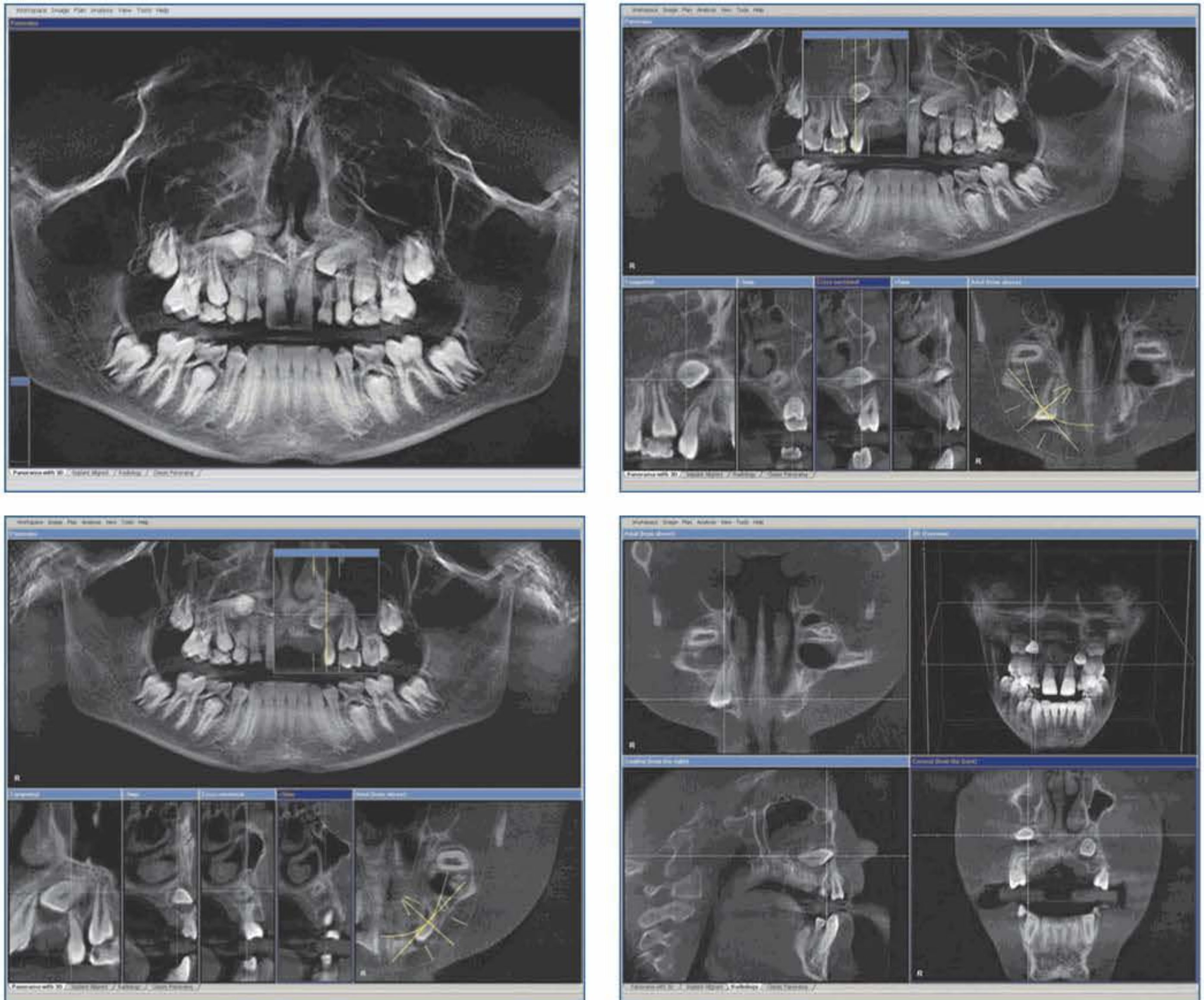


Fig 4-14 A 12-year-old boy with agenesis of teeth 12 and 22 and high horizontal displacement of teeth 13 and 23. The high displacement of teeth 13 and 23 seen in the panoramic view can be clearly identified in the transverse slices. The 3D image and the axial, sagittal and coronal slices permit a comparison of the displaced teeth and an assessment of their suitability for orthodontic correction. In the coronal slice, the root distortion of the maxillary right premolar because of the displacement is particularly visible.

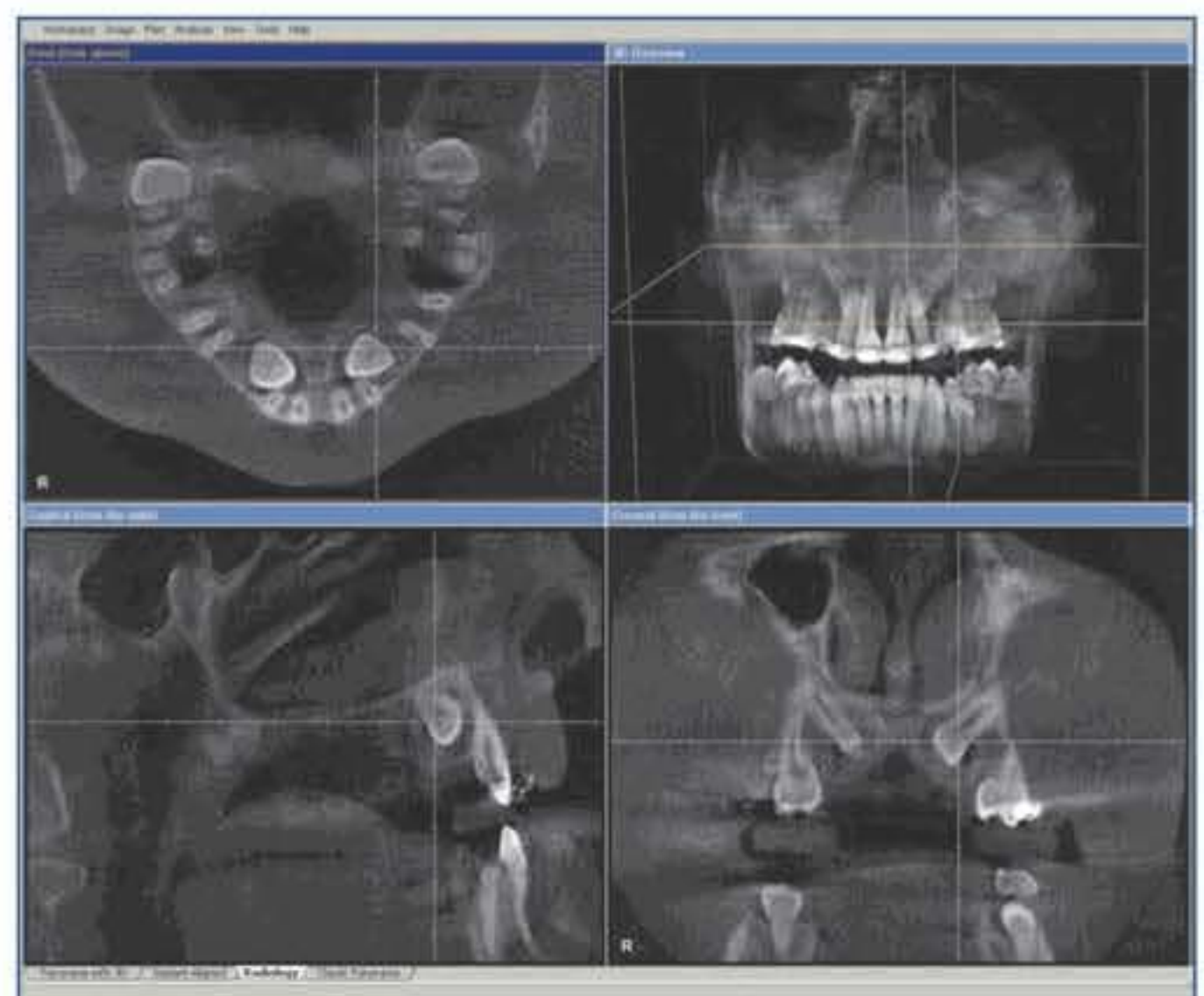


Fig 4-15 A 14-year-old boy with palatal displacement of teeth 13 and 23 and adequate arch space. An enlargement of the follicle of the ectopic cuspids and the direct palatal contact of teeth 12 and 22 have not resulted in root resorptions at teeth 12 and 22. The active orthodontic correction can be more efficiently planned using 3D diagnostics; it involves a palatal movement followed by a distal movement of the ectopic cuspids.

4.2.3 Ectopic Mandibular Cuspids

The less-common displacement of the mandibular cuspids can extend to the mandibular border. The transverse orientation of the tooth and its position in the bone structure can be determined in the 3D image. If a tooth is located in the compact cortex, it must first be moved towards the spongiosa, facilitating orthodontic correction (Figures 4-16 and 4-17).

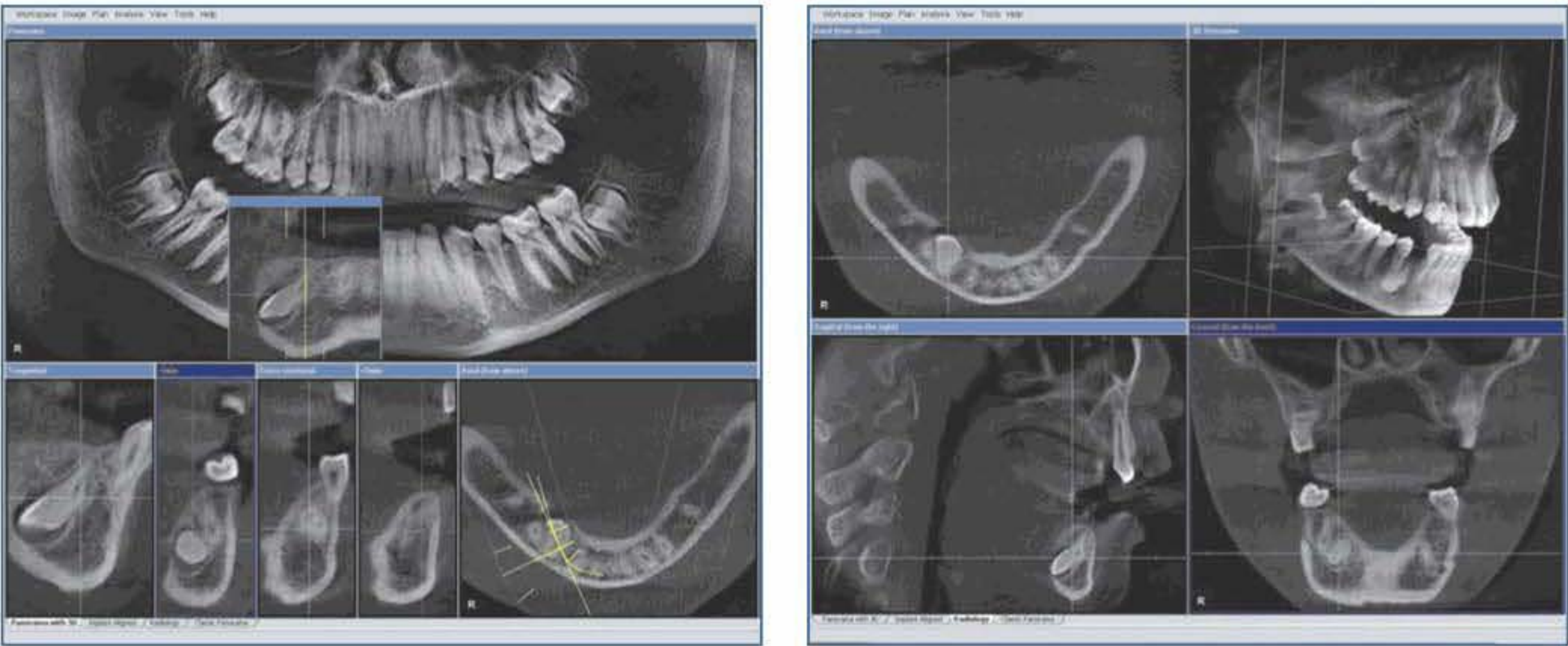


Fig 4-16 A 13-year-old girl with ectopic tooth 43 following childhood mandibular and collum fracture. The ectopic tooth cannot be orthodontically corrected because of its 180-degree inversion. In addition to its distolingual displacement, which is revealed in the axial and sagittal slices, its position relative to the nerve canal is represented in the coronal slice.

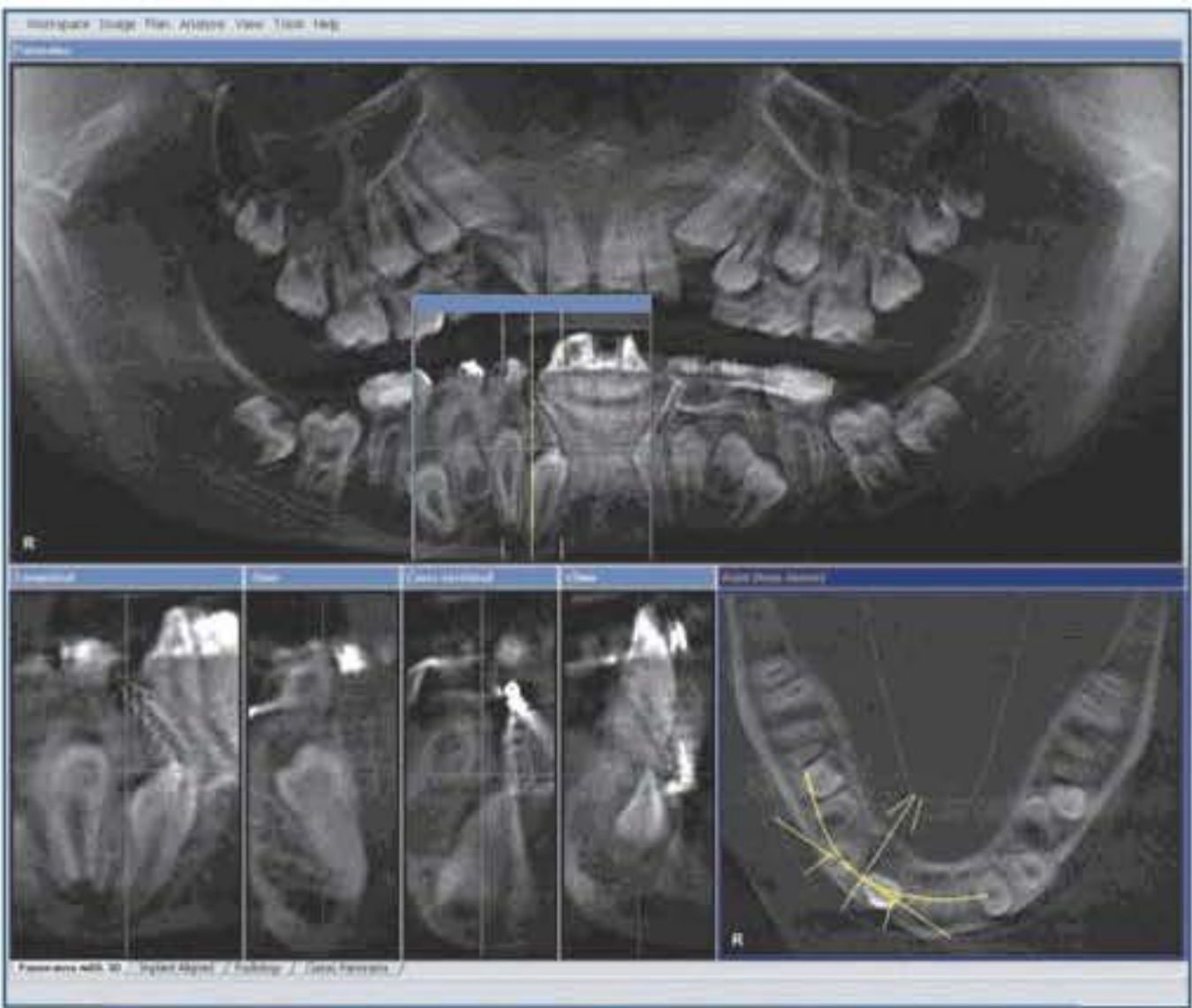


Fig 4-17 A 13-year-old boy with ectopic 33 and 43 and cleidocranial dysostosis. The direct buccal contact between teeth 33 and 43 and the adjacent teeth 32 and 42 revealed in the 3D diagnostics, and the apical crowding of the anterior tooth roots, directly influenced the therapeutic approach. The cuspids were first distanced from the incisors, and in the second step the roots of the incisors were aligned.

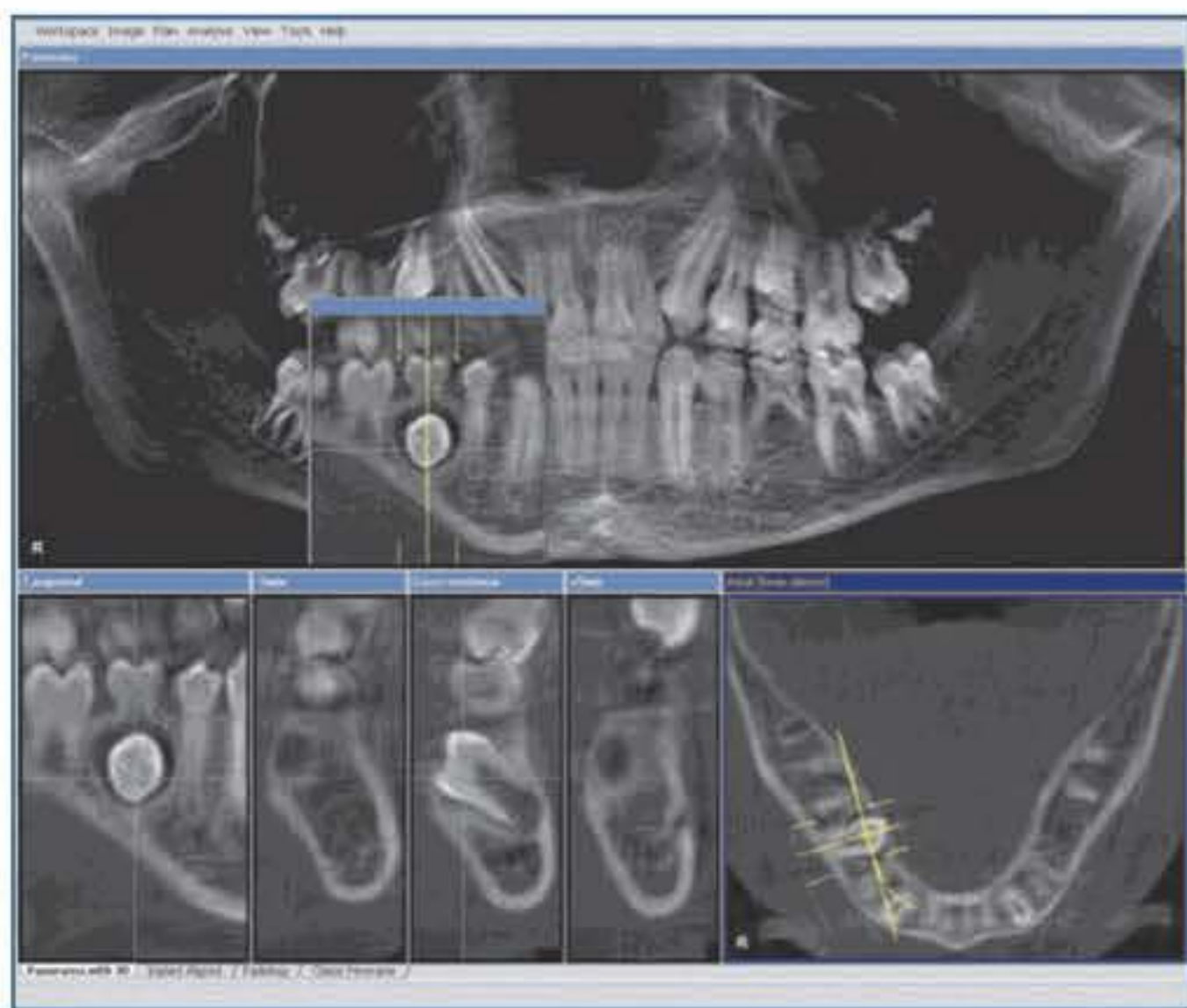


Fig 4-18 A 12-year-old girl with undefined displacement of tooth 45 with questionable suitability for orthodontic correction, and agenesis of tooth 35. The lingual tipping of 45 and the cortical position of its corona are impressively represented in the axial and transverse view and so the previously uncertain prognosis was not confirmed and orthodontic correction was possible.

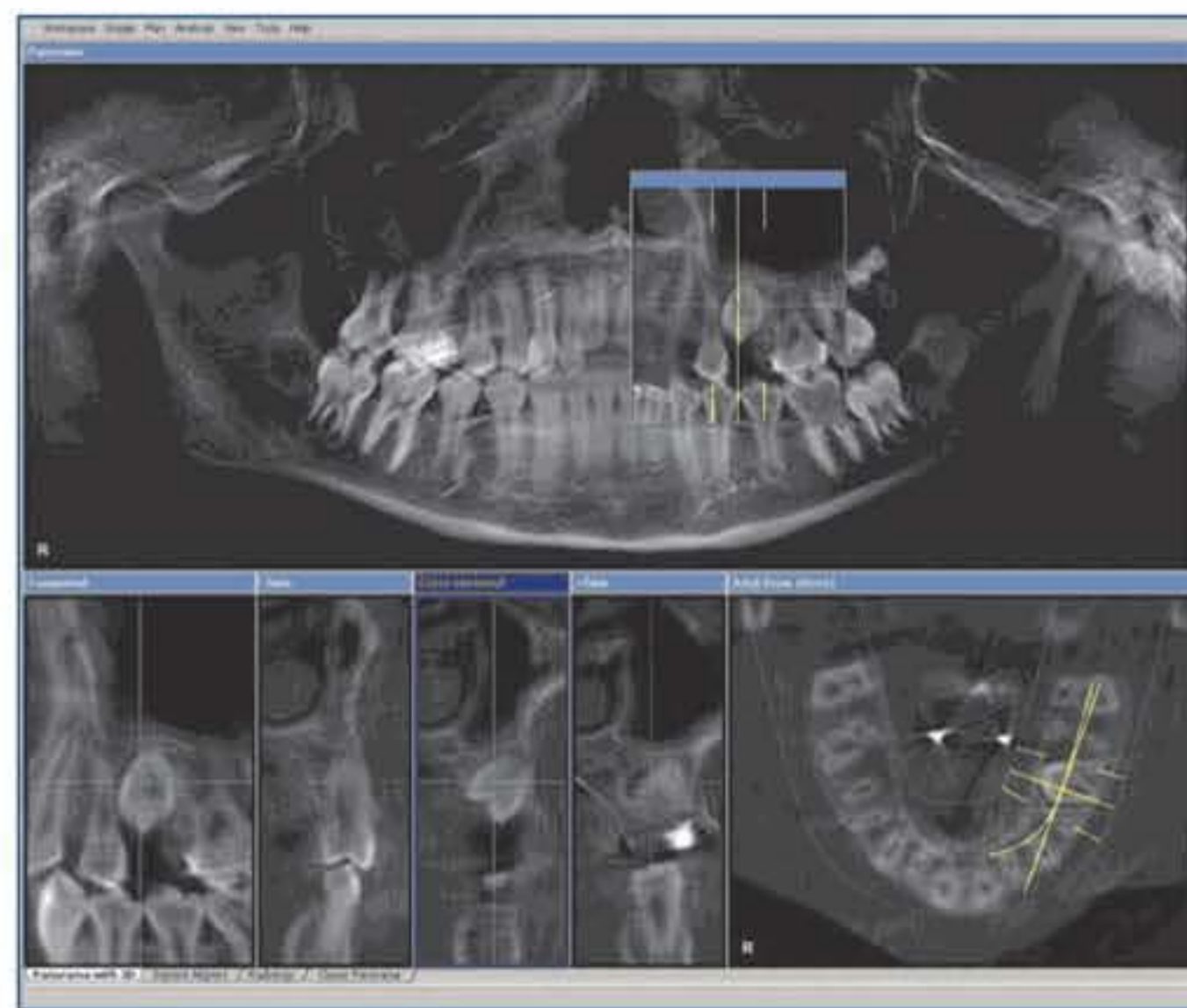


Fig 4-19 A 12-year-old girl with ectopic tooth 25 and after attempted orthodontic correction of tooth 25 with a fixed appliance for six months. The transverse and axial slices revealed a palatal tilt of the tooth with displacement of the shortened root into the buccal cortex and a deep maxillary sinus, which could have caused the correction difficulties regarding tooth 25.



Fig 4-20 A 10-year-old boy with ectopic tooth 35 and agenesis of tooth 45. The distolingually displaced tooth bud of 35 exhibiting delayed mineralization was allowed to remain at the time of imaging, postponing a decision on potential orthodontic correction of this tooth subject to the root development seen in subsequent images.

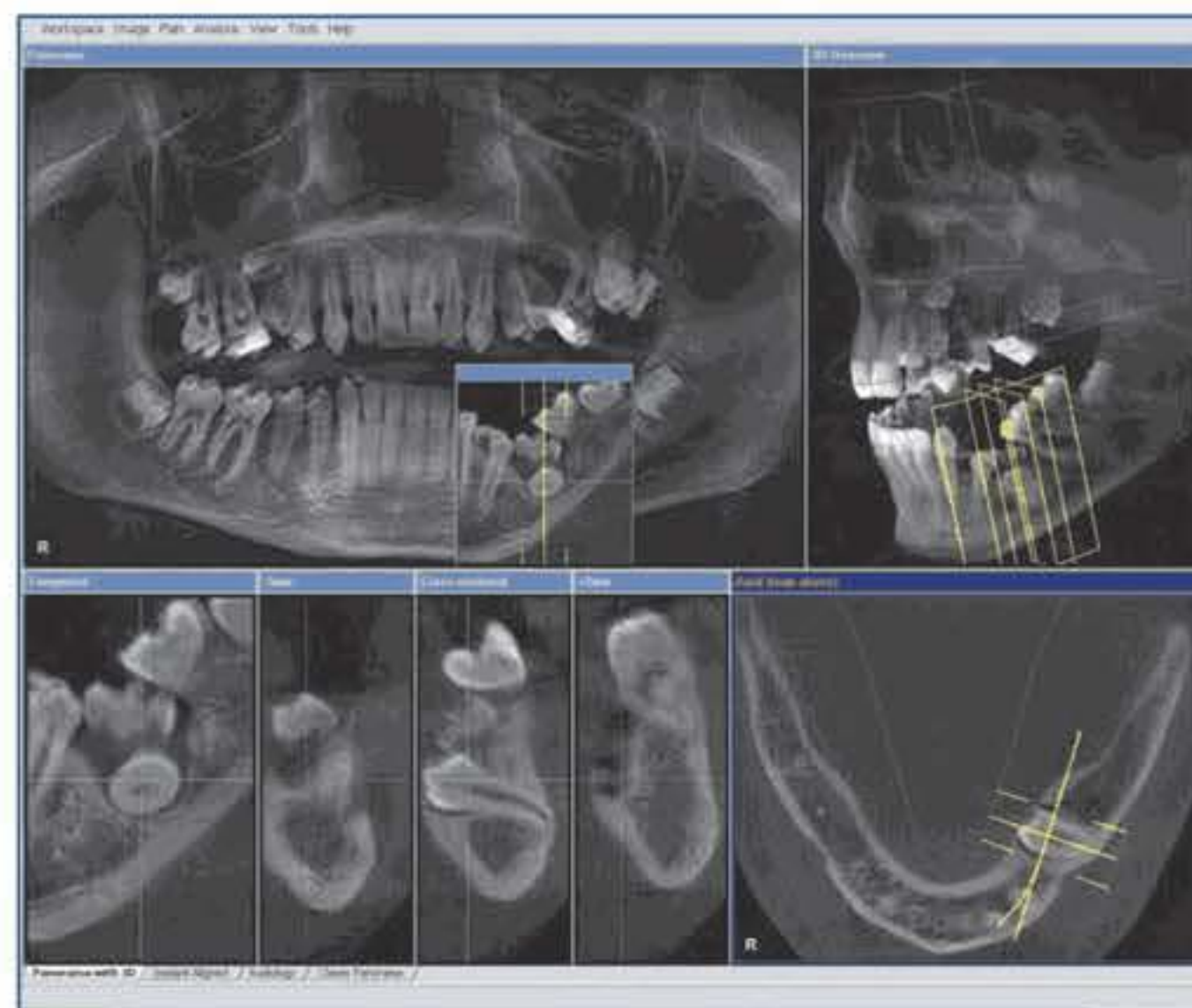


Fig 4-21 A 13-year-old boy with a supernumerary tooth in the region of tooth 15 and eruption disturbances in the regions of 25, 35 and 34. The teeth were located in transverse and tangential slices and the position of tooth 15 relative to the maxillary sinus could be assessed for planning the surgical removal of the teeth. After removal of tooth 26, which was destroyed by caries, teeth 25 and 27, the horizontally displaced 35 and the impacted 34 could be orthodontically aligned.

4.2.4 Ectopic Premolars

Ectopic premolars frequently occur at the end of the primary dental ridges. They can be associated with supernumerary teeth. Because of their location at the transition of the dental ridges, displacements may range from mild manifestations to inversions of the tooth germ (Figures 4-18 to 4-21).

4.2.5 Ectopic Molars

With the exception of the wisdom teeth, ectopic molars are rare and are associated with ectopic adjacent tooth germs (Figures 4-22 and 4-23).

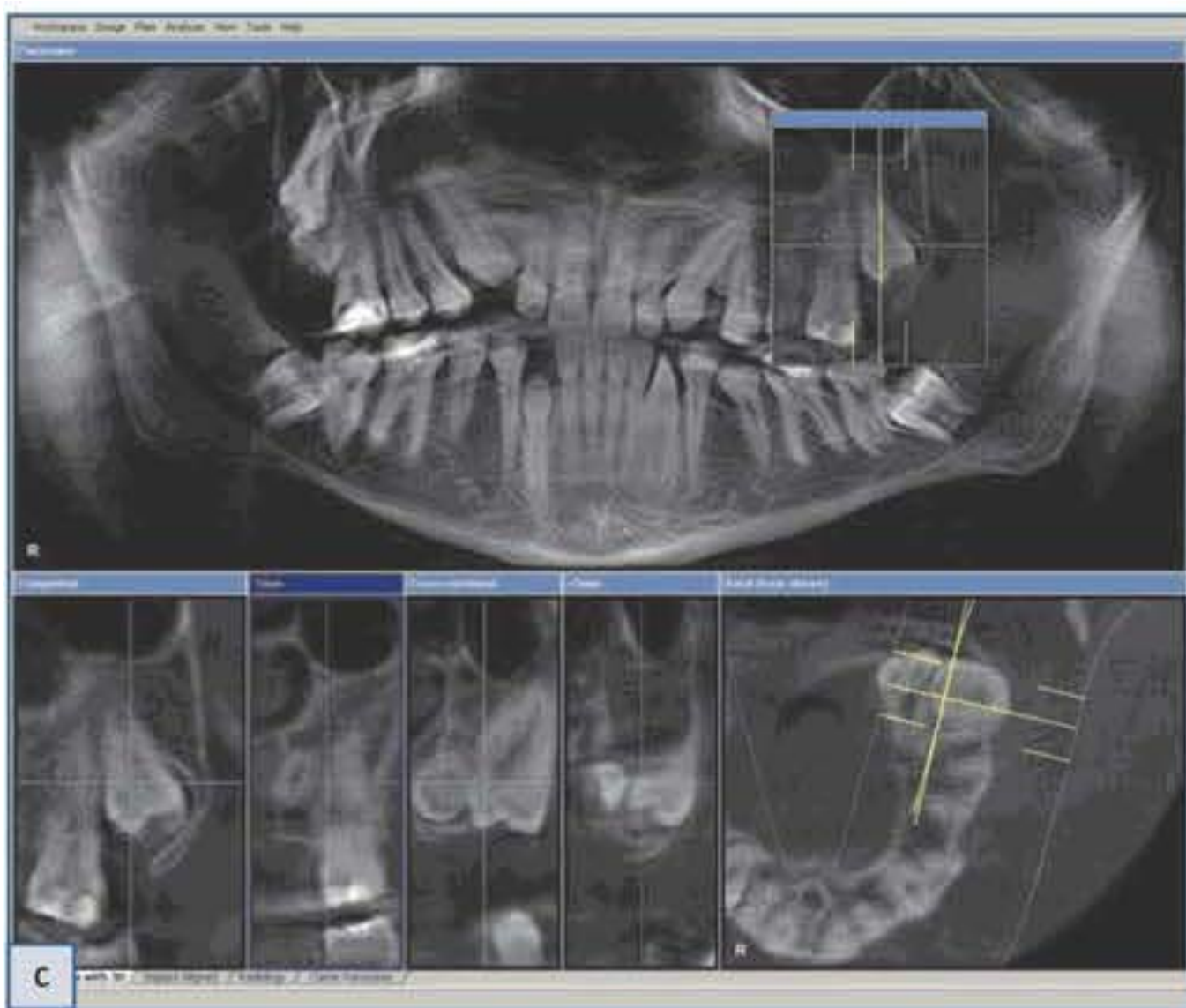


Fig 4-22 The three frames show images for a 19-year-old male with eruption disturbance of 13, 23, 33 and 43, and of 17 and 27, with ectopic 18 and 28. The panoramic view showed a diffuse opacity in the region of teeth 17 and 27. Further 3D imaging in axial view demonstrated palatal displacement of teeth 18 and 28 and impaction of teeth 17 and 27. The root development of the impacted 17 and 27 was so advanced that prompt extraction of teeth 18 and 28 and active correction of teeth 17 and 27 with concurrent correction of teeth 13, 23, 33 and 43 was planned.

Fig 4-23 A 21-year-old male with eruption disturbance of tooth 37. The tangential and transverse slices revealed the cortical position of the mesial root of tooth 37 and its retention.

Fig 4-24 An 18-year-old female after several years of orthodontic treatment at another center, with attempted correction of teeth 16 and 46, which exhibited eruption disturbances. After treatment of 46 had failed, the 3D image revealed a lingual bend of the roots, complicating orthodontic correction. Despite the immediate proximity of the roots to the mandibular canal revealed in the transverse slices, the patient opted for surgical correction of the impacted teeth by segment distraction.



Fig 4-25 A 14-year-old female with impacted 36 and visible ankylosis.

4.3 Eruption Disturbances and Ankyloses

There are different reasons for permanent teeth to remain completely in the jaw bone. Ankylosis occasionally occurs following trauma in which teeth were luxated or replanted. Often, a growth disorder of the alveolar process in the region of the teeth exhibiting eruption disturbances is found. Single teeth or entire groups of teeth may be affected.

Ankylosed teeth do not exhibit a periodontal space. They frequently cause growth disturbances and remain in infraposition. Potential orthodontic correction of the tooth should be carefully investigated before any therapy decisions are made (Figures 4-24 to 4-26).

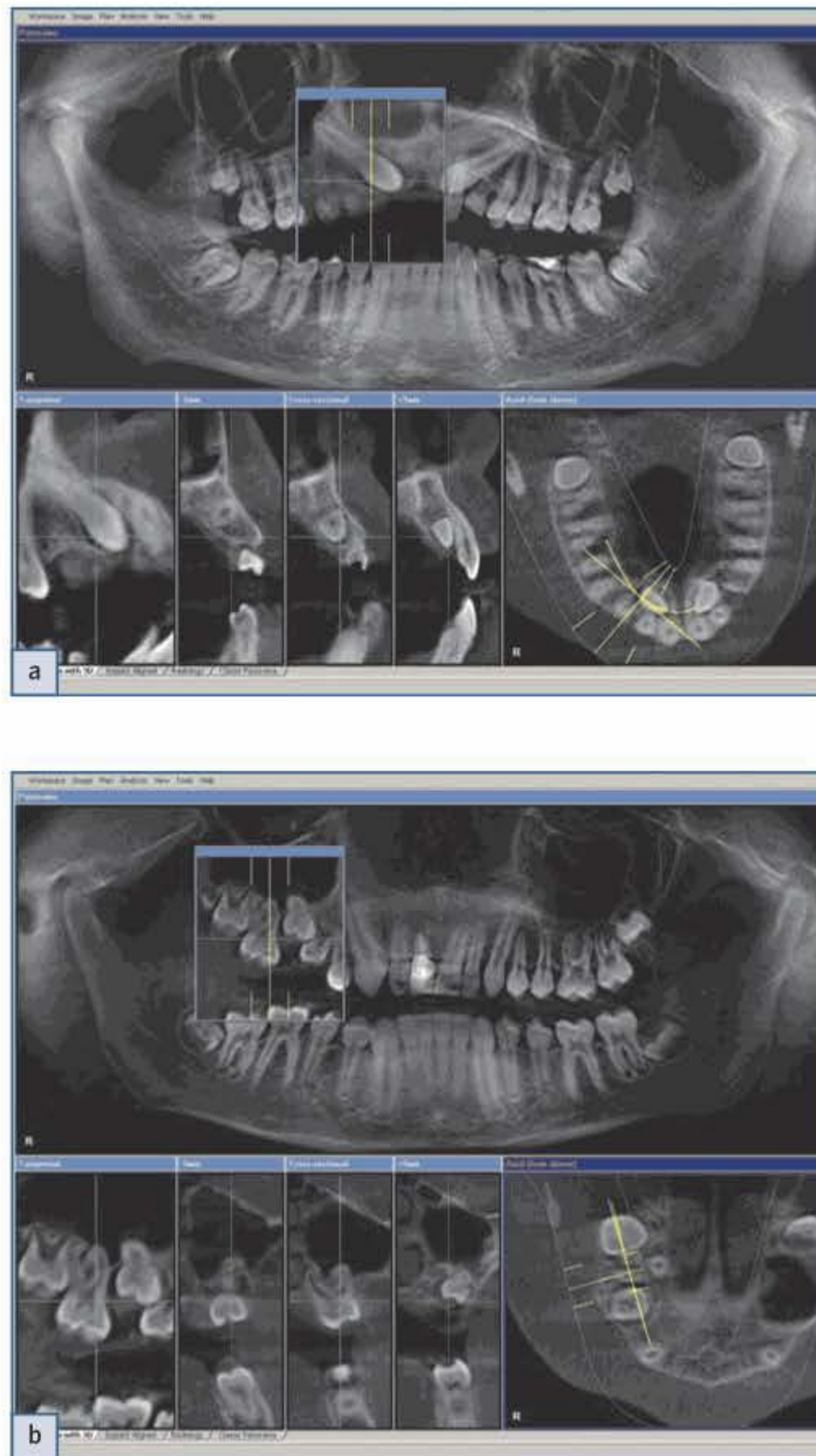


Fig 4-26 A 14-year-old male with growth disturbance and eruption disturbance in the region of teeth 16 and 17 and eruption disturbance of tooth 55 located at the level of the maxillary sinus, with resulting displacement of the 15 tooth bud. Secondary findings included inadequate root filling with apical lucency at tooth 11, which had been damaged by trauma.

4.4 Resorption of Adjacent Structures

In ectopic teeth, the assessment of adjacent structures is very important. Resorption processes can occur both in the crown and in the root region of adjacent teeth and may extend into the pulp, critically affecting therapy.

The most prevalent resorption is found in those with ectopic cuspids and affects the lateral maxillary incisors. The slice images in 3D imaging permit early recognition and accurate assessment of the extent of resorption on adjacent structures. Resorption frequently affects the palatal and distal surfaces of adjacent teeth and can extend into the pulp. If pronounced apical or lateral resorption is found, therapy may include extraction of the resorbed teeth (Figures 4-27 and 4-28).

Fig 4-27 A 13-year-old girl with ectopic 13 and 23. The significant mesial displacement has resulted in pronounced root resorptions on the lateral incisors, revealed in the transverse slice at tooth 12. Based on the radiological findings, teeth 12, 22 were therapeutically extracted and the ectopic teeth 13 and 23 were moved into the region vacated by teeth 12 and 22.

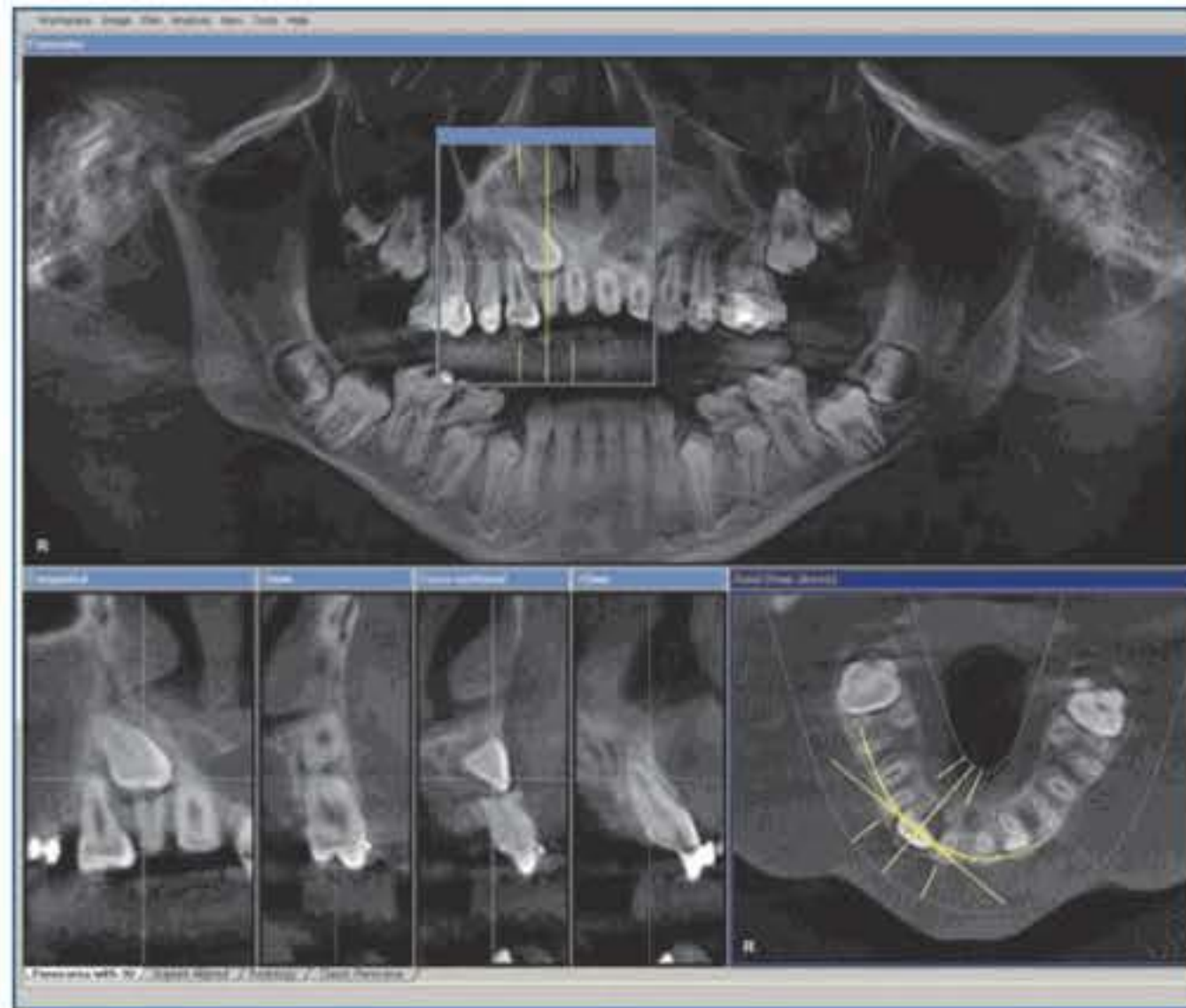
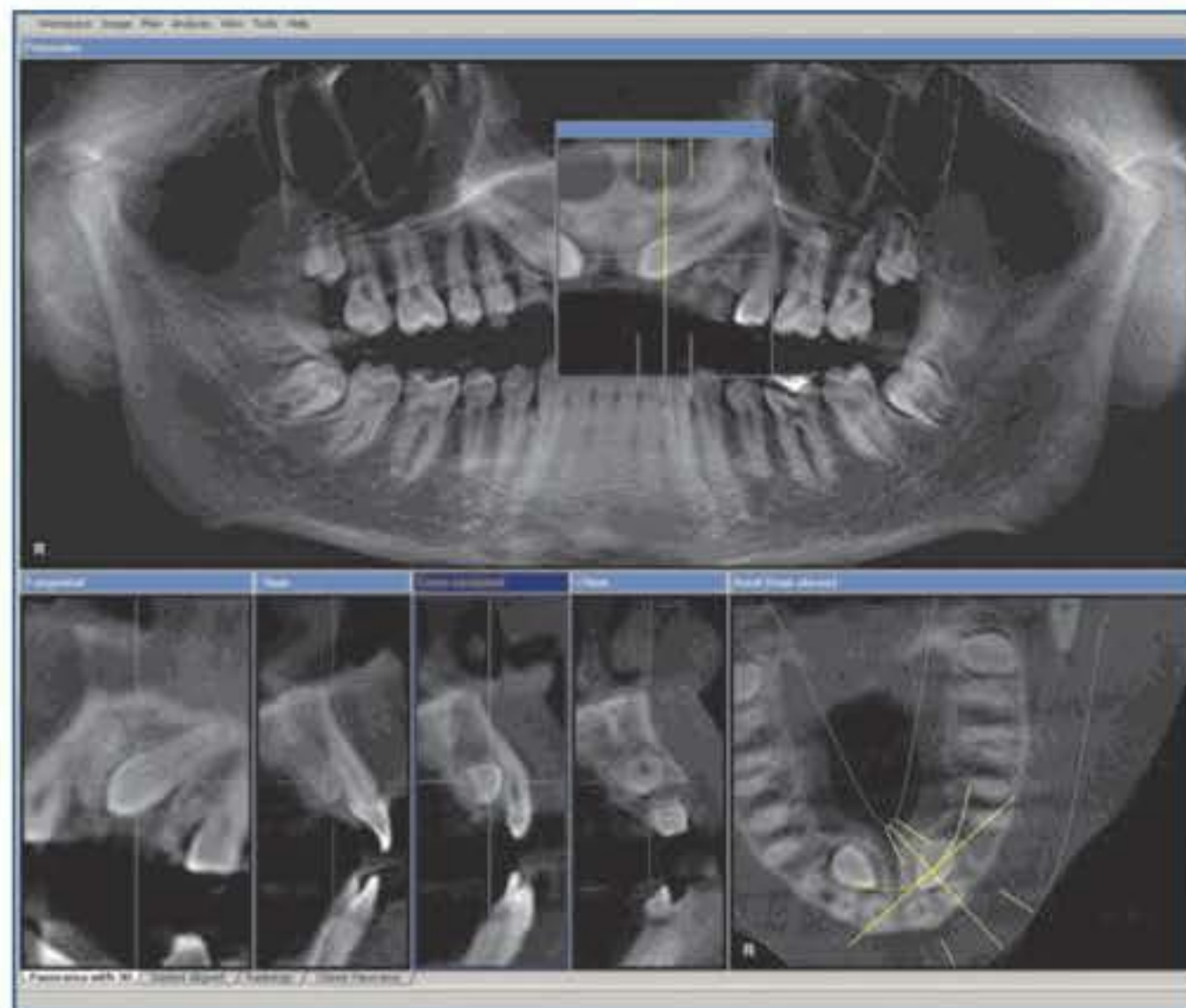


Fig 4-28 An 18-year-old male with palatal displacement of teeth 13 and 23 and tight topographic relationship of the teeth to the adjacent teeth 12 and 22. The transverse slices reveal initial resorption processes at the palatal surfaces of teeth 12 and 22.



4.5 General Eruption Disturbances

In general, eruption disturbances are identified before completion of skeletal growth using early and comprehensive orthodontic diagnostic methods. As a result, these teeth are successfully integrated into the dental arch in many cases. However, if orthodontic treatment methods are not available or not implemented during adolescence, retained teeth frequently remain in the jaw for decades without exhibiting distinctive clinical features. Constant long-term loading may then result in perforations, caries or cyst formation, depending on the fixation of a prosthetic tooth replacement (Figure 4-29).

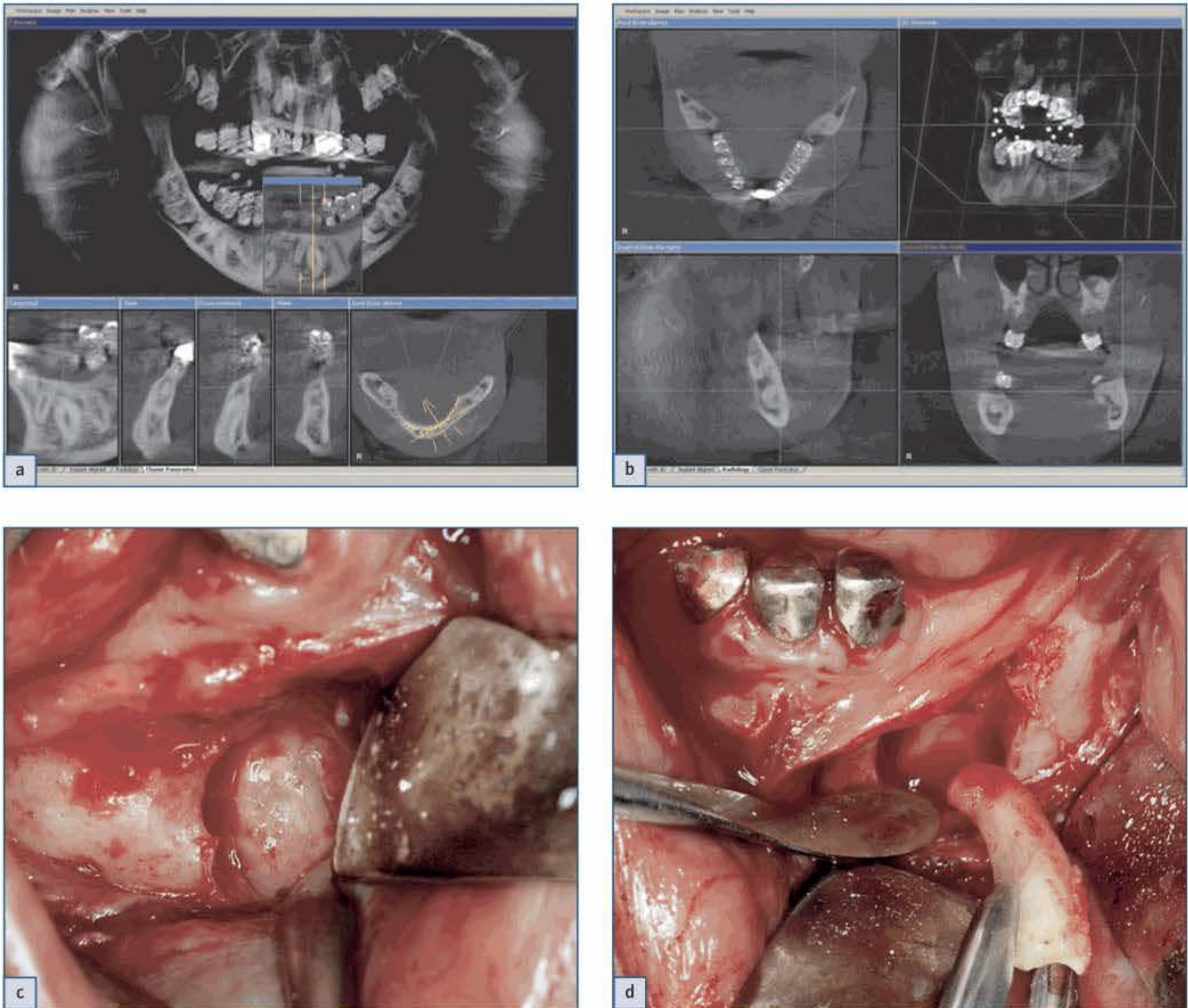


Fig 4-29 A 62-year-old patient with inadequately supported dental prosthesis and onset of functional symptoms in the region of the muscles of mastication on the left side. The prosthetic appliance was supported by teeth 14, 21, 24 and 25 in the maxilla and by 31, 41 and 42 in the mandible. The other teeth were missing, impacted or ectopic. (a) The scan, performed using a BaSO₄ template, was used for planning the placement of additional implants designed to secure the prosthesis, so that an exclusively tegumentally supported dental replacement could be avoided. Osteotomy of teeth 33, 32 and 43 was planned for anchoring a bar-supported overdenture. (b) The assumed cystically altered tooth 38 to which the functional symptoms in the left temporomandibular joint were attributed exhibited an unremarkable position in the bone in the absence of cyst formation; in consultation with the patient, an osteotomy was not performed. (c) Described osteotomy of retained teeth 33 and 43 without visible pericoronal soft tissue for minor traumatization of the future implant area. (d) Conservative luxation in preparation of defect augmentation with free iliac crest bone graft.

4.6 Summary

The various manifestations of eruption disturbance require an accurate determination of tooth position relative to the adjacent anatomical structures. Three-dimensional diagnostics permit accurate determination of positional relationships and facilitate a prognosis regarding the course of

continuing therapy. This eliminates the need for positional determination using the preparation of different single images, often with eccentrically oriented beams or in several planes. These imaging combinations will engender some uncertainty regarding the projection direction and they rarely permit an accurate metric analysis or inform about the tissue structure for an assessment of bone quality or the width of the periodontal space.⁷ In orthodontic treatment planning, the assessment of the position and degree of ankylosis of the impacted tooth, of bone quality and of spatial relations permits a prognosis for successful orthodontic adjustment. An accurate metric analysis facilitates a decision regarding the orthodontic correction of the teeth versus their surgical extraction. If surgical interventions are required, 3D imaging permits accurate surgical planning, and the patient can be shown visually the potential risks. The extent of surgery can be determined preoperatively, based on the characteristics of the ankylosis, and the operative risk can be assessed. By virtue of accurate metric diagnostics, surgery can be optimally prepared and the surgical access can be planned to protect tissue.¹² Depending on the degree of displacement, navigation-guided surgery can be used for a minimally invasive surgical approach. The resulting spatial orientation shortens the surgical time and reduces the degree of postoperative symptoms.⁵

4.7 References

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5 Pathological Bone Lesions

Martin Scheer and Robert A. Mischkowski

Cysts are single-chambered or multichambered hollow spaces in the jaw that are lined with epithelium. The nurturing connective tissue is found beneath the epithelium; together, they form the cyst wall. The division of epithelial cells results in degeneration of the cells that are farthest away from the vascular connective tissue. Because of the increase in the osmotic gradient inside the cyst, fluid enters; this, in turn, results in pressure-induced atrophy of the surrounding bone.

Jaw cysts can arise from tissues of the dental system (odontogenic cysts) and may be developmentally associated cysts or pseudocysts. According to the World Health Organization (WHO) classification of 2003, epithelial cysts can be developmental odontogenic or non-odontogenic and are classified separately from inflammation-associated cysts. Aneurysmal and traumatic (pseudo-) cysts are classified as non-neoplastic bone changes.¹

The most common cyst type is inflammation-associated cysts (radicular cysts; 56.9%). Follicular cysts and keratocystic odontogenic tumors (keratocysts) are seen significantly less frequently (21.3% and 10.6%, respectively).² Odontogenic tumors such as ameloblastoma are found in 4.1% of cystic jaw changes.² In the vast majority of cases, cysts are clinically symptomless. Distentions of the jaw or of facial soft tissues are only visible with increasing cyst size. Inflammatory symptoms may arise from infection of the cyst lumen. In addition, pathological fractures caused by the weakening of the bone, primarily the mandible, can cause symptoms such as occlusion disturbance, pain and hyperesthesia. In diagnosis, the pulp vitality test is used in addition to inspection and palpation of contour changes and malpositions of the teeth. Radiological examination in at least two planes is indispensable for advanced diagnostics. Table 5-1 gives the criteria that can be used for type diagnosis and establishing a working approach.³ In the great majority of cases, cysts are only identified in a panoramic radiograph (OPG). In conventional x-ray images, cysts appear as smoothly bordered, roundish, sometimes multichambered lucencies with radiopaque margins. When there is intense inflammatory activity, this margin may be absent.³ Poor demarcation of the lucency should always prompt consideration of the rarer changes such as odontogenic tumors,

Criterion	Parameter
Locality within the mandible	Symphysis, body or ascending ramus
Relationship to adjacent teeth	Involvement of the root or corona of the involved tooth
Shape of the lesion	Round or oval shape, digitiform extension between the tooth roots
Degree of radiopermeability	Lower in keratocysts owing to corneal masses
Demarcation of the cyst from surrounding bone	Sharp or blurred
Lesion margin	Sclerotic margin or enhanced bone remodeling
Expansion into the soft tissues	Buccolingual expansion, preservation of the anatomical bone contour in the mandible
Septation	Partial or complete septation (unilocular or multilocular lesion)

Table 5-1 Radiological criteria for the diagnosis of cysts, modified according to Weber.³

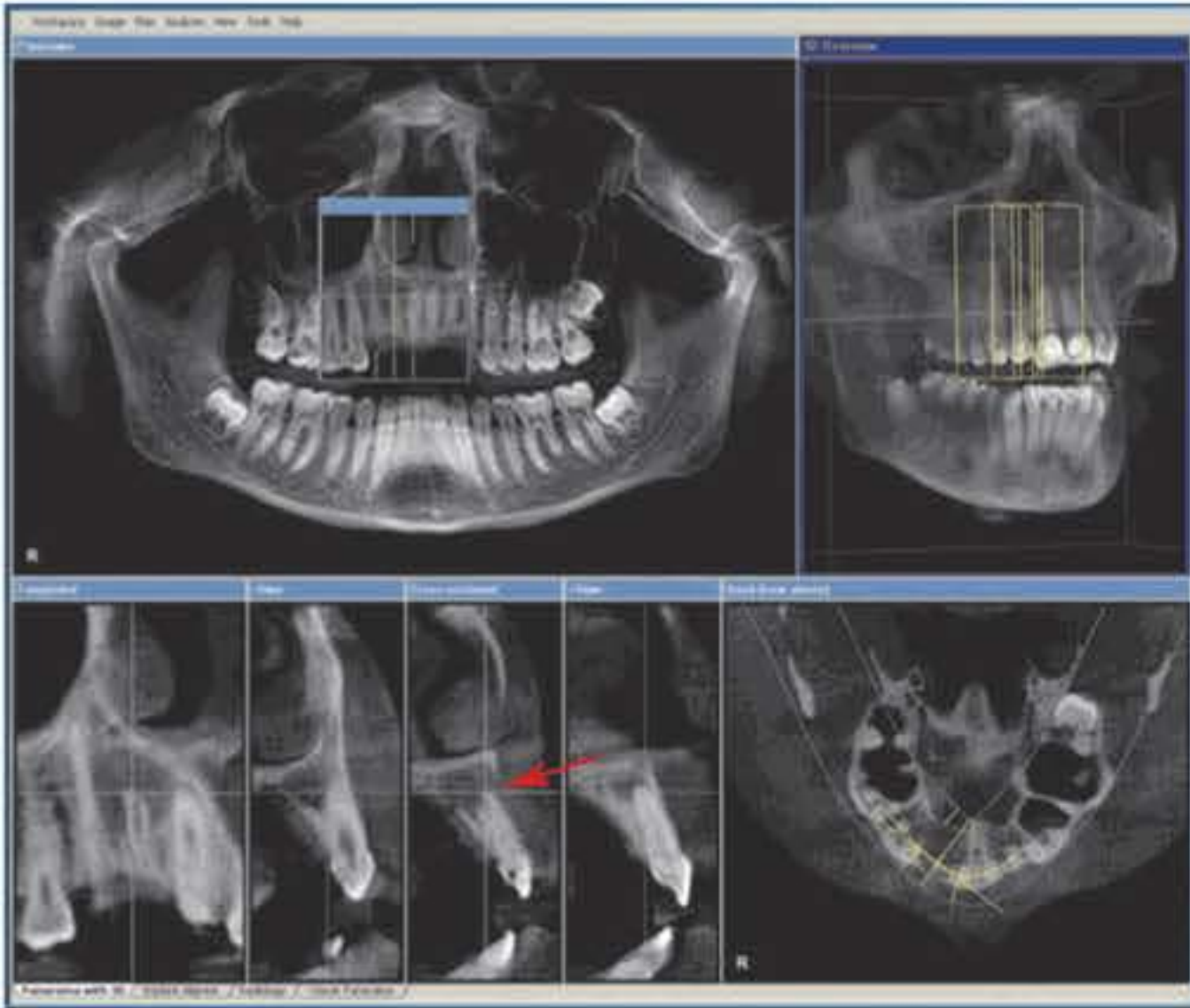


Fig 5-1 Radicular cyst in the right maxilla of a 17-year-old female patient, originating from 12, with lysis of the vestibular cortical bone (arrow) in the transverse slice.



Fig 5-2 Radicular cyst in the mandible, originating from the mesial root of 46. The lingual osteolysis and the relationship to the nerve canal are revealed in the coronal slice (arrows).

metastases, plasmocytomas and osteosarcomas in the differential diagnosis. In individual cases, further radiological procedures such as CT and MRI may be required for therapy planning, particularly if an extensive area is affected or the lesion is close to anatomical structures such as the nasal floor, the maxillary sinus or the inferior alveolar nerve.

5.1 Inflammatory Cysts

5.1.1 Radicular Cysts

Radicular cysts are some of the most common cystic changes in the jaw (Figures 5-1 and 5-2). Cyst growth occurs via an inflammatory reactivation of epithelial rest cells of Malassez in apical granulomas. Most affected patients are male and between 30 and 50 years old. Radicular cysts mainly occur in the anterior maxilla.⁴ In addition to apical cysts, lateral variants are also known. Radiographically, radicular cysts are identified by a smoothly demarcated, roundish, unilocular osteolysis, surrounded by a sclerotic margin that may be absent in severe inflammatory activity. In individual patients, the lamina dura of the affected tooth may be attached to the wall of the cyst. Radicular cysts can result in the displacement of adjacent teeth. Periapical granulomas and radicular cysts are differentiated by size. Lesions under 5 mm in diameter are granulomas.

5.1.2 Residual Cysts

Cyst regrowth can occur if the treatment of the radicular cyst is inadequate at the time of extraction or root canal treatment of the affected teeth. Residual cysts almost exclusively arise from radicular cysts.⁴ The medical history can provide critical clues to differentiating them from keratocysts.

5.2 Developmental Odontogenic Cysts

5.2.1 Follicular Cysts

Follicular cysts arise from the non-keratinized enamel epithelium of teeth that have not yet erupted (Figures 5-3 to 5-6). Follicular cysts are seen more frequently in males than in females, with a peak incidence at 20 to 40 years of age. The most common sites are the wisdom tooth and premolar region in the mandible and the region of the cuspids in the maxilla.⁵ The radiographic criteria for follicular cysts include a clearly demarcated unilocular radiolucency into which the corona of an unerupted tooth projects. Follicular cysts are also seen in the absence of teeth. Increasing growth can result in migration of the causative tooth toward the basal cortical bone. In contrast to keratocystic odontogenic tumors, follicular cysts do not perforate the cortex of the mandible. Nevertheless, the mandible is often extensively involved in the antero-posterior direction. The potential development of ameloblastoma, mucoepidermoid carcinoma and squamous cell carcinoma are discussed later in this chapter.

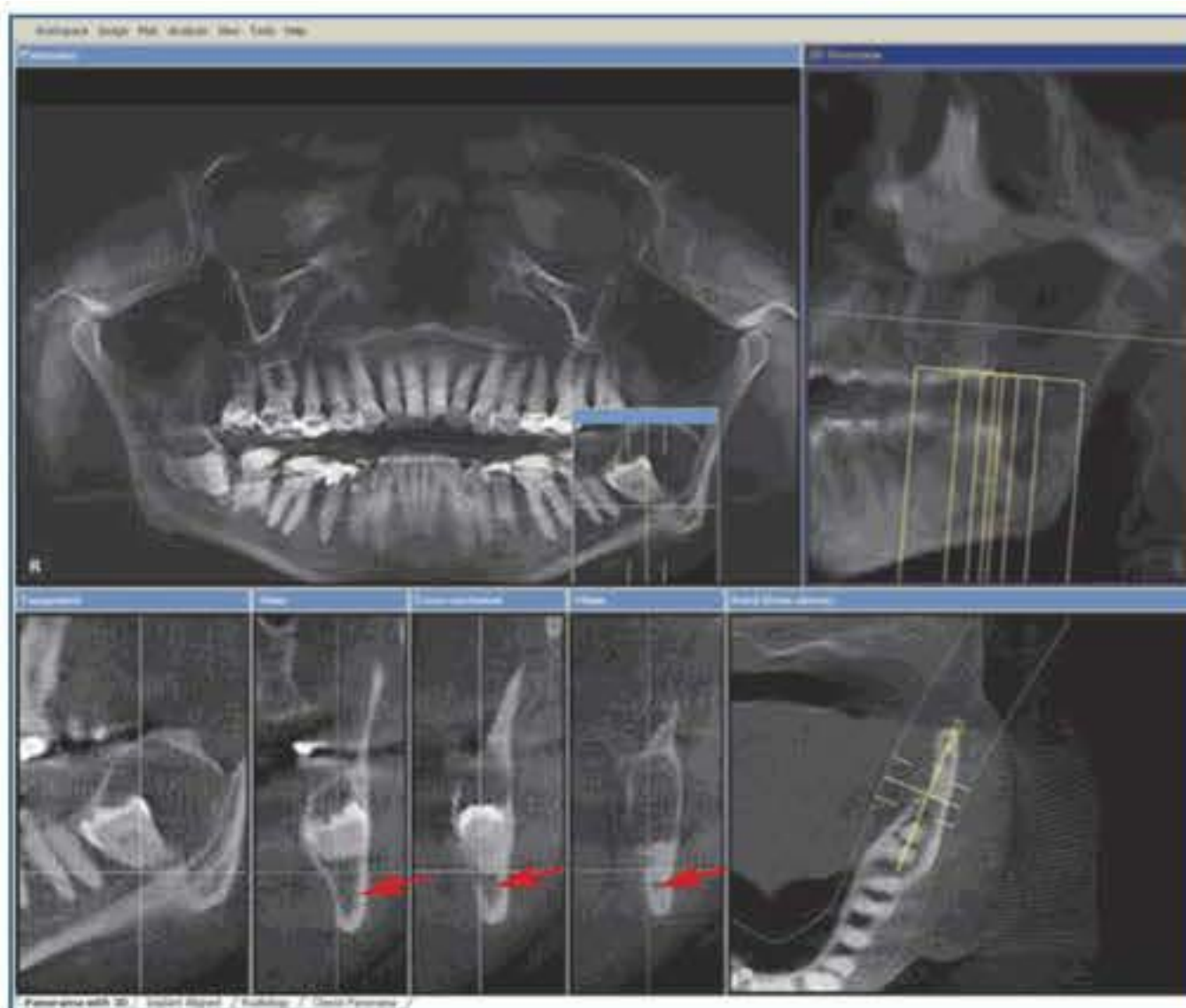


Fig 5-3 Unilocular follicular cyst originating from a 38 with eruption disturbance. The course of the inferior alveolar nerve lingual to the root tip of 38 can be identified on the transverse slices (arrows).

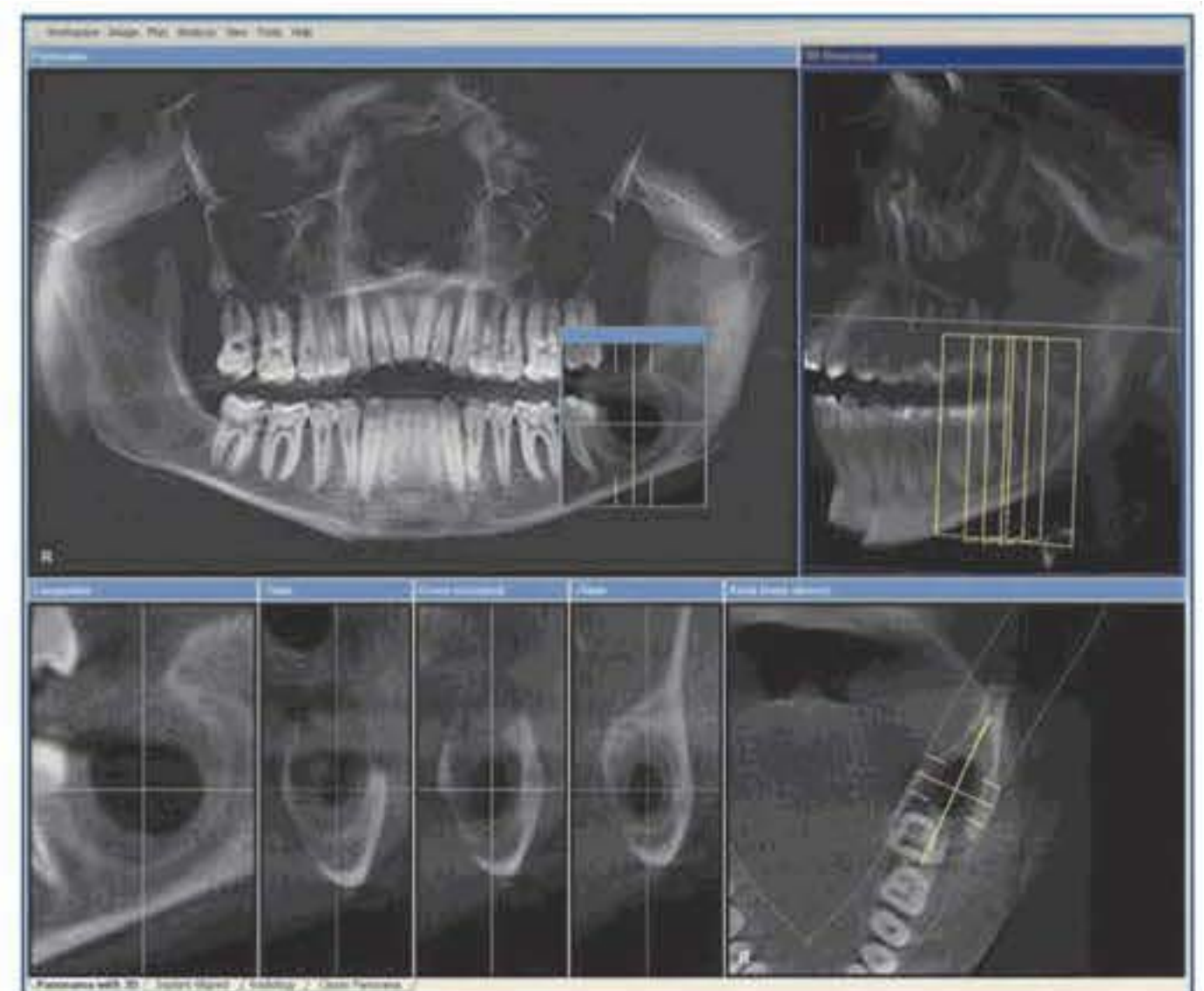


Fig 5-4 Follicular cyst in the region of 38 in a 16-year-old male. The cyst is no longer crestally bordered by bone after cystostomy.

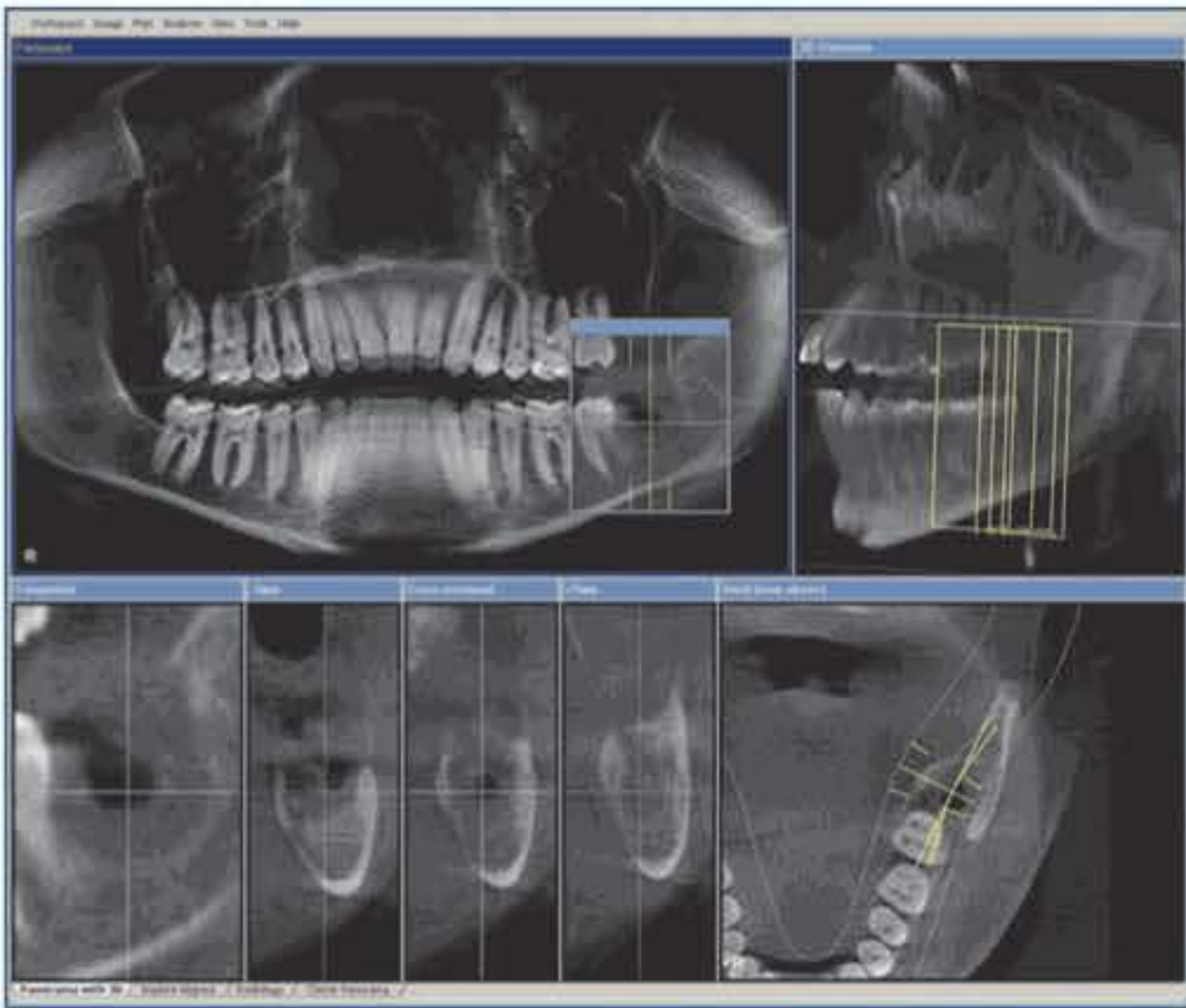


Fig 5-5 The same patient as in Fig 5-4 after a two-week strip change three months later. A reduction of the cyst lumen can be identified in the orthopantographic view and in its transverse slices.

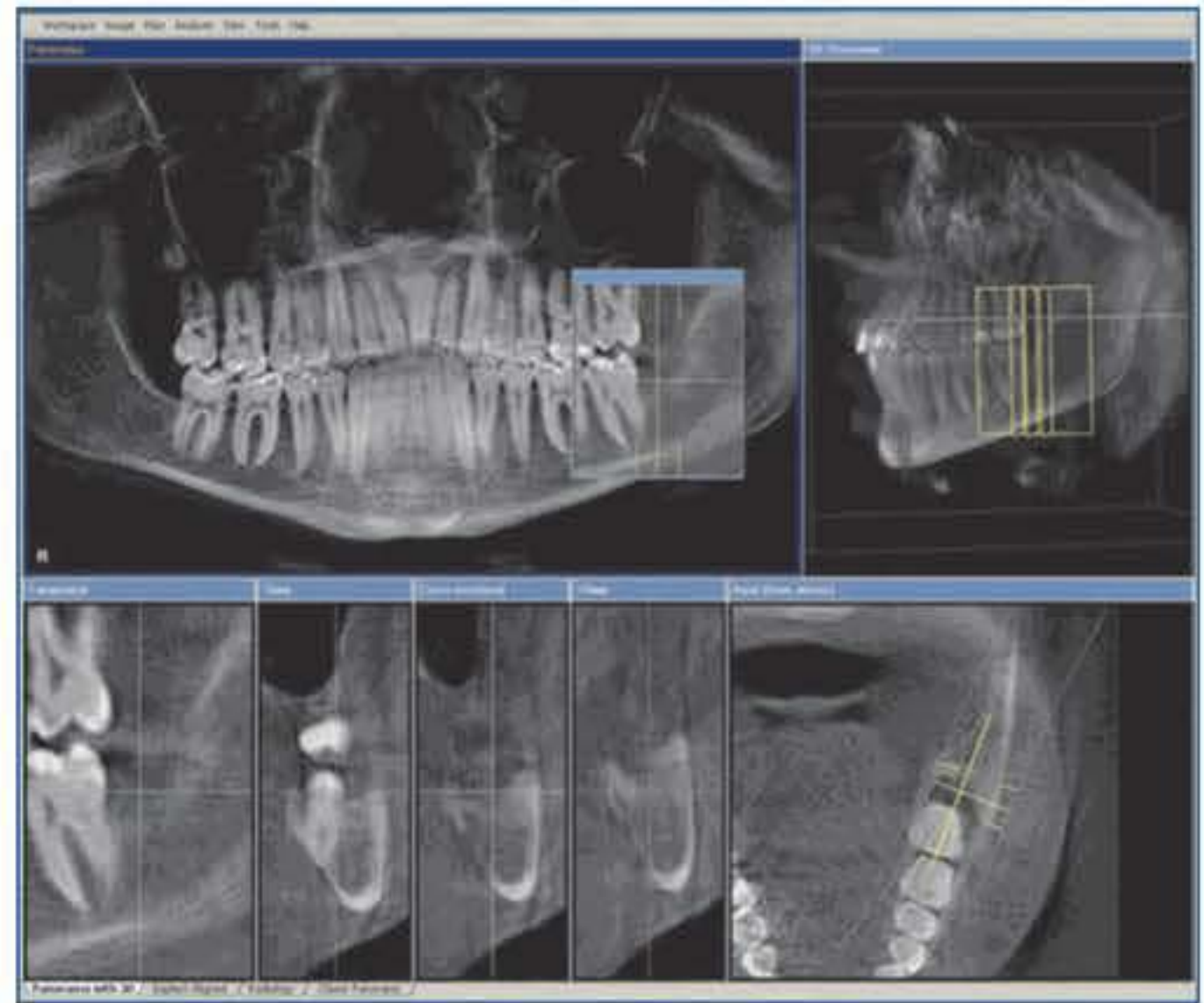


Fig 5-6 The same patient as in Figs 5-4 and 5-5, another three months later. The almost complete osseous regeneration of the former cyst lumen is revealed in the orthopantographic view.

5.2.2 Keratocystic Odontogenic Tumor (Formerly Keratocyst)

The keratocystic odontogenic tumor is a cystoid neoplasm lined with a thin fibrous capsule and parakeratinized squamous epithelium arising from epithelial rests of Serres (Figures 5-7 to 5-9).¹ It primarily affects males between 20 and 30 years of age. In the x-ray image, keratocystic odontogenic tumors appear as potentially unilocular but primarily multilocular ("satellites") extensive osteolysis in the mandibular angle, in the ascending ramus of the mandible and in the cuspid region. These tumors can occur with retained teeth (follicular type), between the teeth (collateral type) and without teeth (primordial type). Resorption of adjacent root tips, displacement of teeth as well as perforation and excavation of the cortex into the surrounding soft tissue demonstrate the aggressive growth of these tumors, which were called keratocysts before the WHO 2003 reclassification.⁶ The literature reports recurrence rates between 20 and 60%.⁷ Some authors consider that the keratocystic odontogenic tumor will appear less lucent than other cysts in x-ray imaging because of its high protein content (exfoliated keratin).⁸ Differentiation can be difficult from ameloblastoma, which also can have multilocular osteolyses, and from follicular cysts, which occur in similar locations and can contain the crowns of retained teeth. However, compared with follicular cysts, the inclusion of the entire corona is more rare in the cystic lucency of keratocystic odontogenic tumors. Rather, keratocystic odontogenic tumors result in a displacement of the entire tooth or tooth bud. Compared with other cysts and pseudocysts of the jaw region, keratocystic odontogenic tumors require more aggressive therapy because they have a recurrence rate of up to 60%. This is attributed to the "daughter cysts" and to the thin, very fragile cyst wall. For this reason, some authors recommend the intraoperative fixing of the cyst sac with Carnoy's solution and the excision of parts of the overlying mucosa.⁹



Fig 5-7 Orthopantomograph of a 36-year-old male with a chambered cystic lucency in the region of 48-46 and impacted and ectopic 38.



Fig 5-8 Orthopantomograph of the same patient six months later. The comparison shows an increased size of the septated cystic change in the region of 48-46.

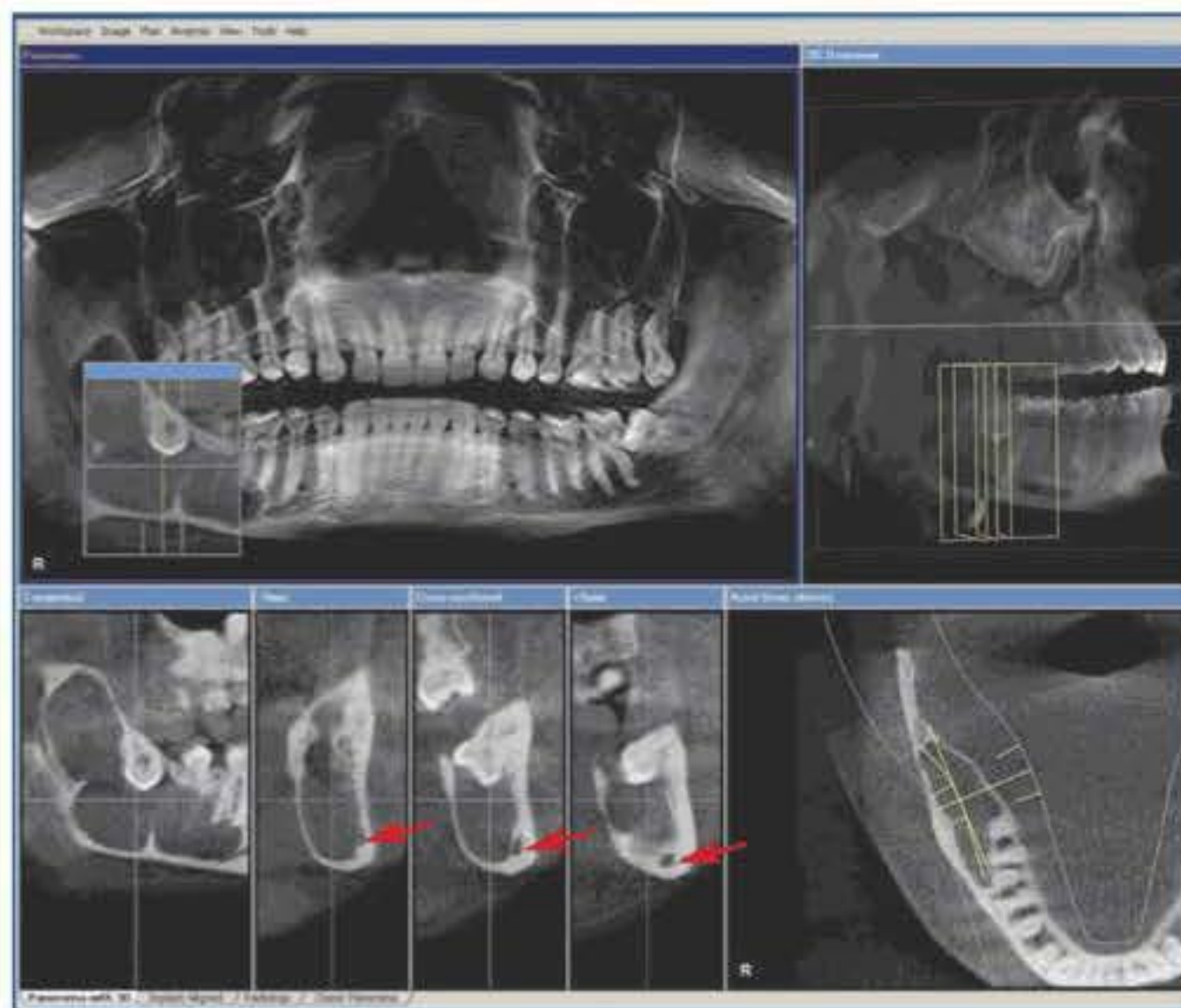


Fig 5-9 Cone-beam volumetric imaging of the same patient as in Figs 5-7 and 5-8, more than four and a half years later. Both the buccolingual and the craniocaudal expansion of the keratocyst in the region of 48-46 can be clearly identified. The inferior alveolar nerve (arrow) can be identified in the transverse and tangential slices.

5.3 Odontogenic Tumors

According to the 2003 WHO classification, odontogenic tumors are divided into benign and malignant variants.¹ Benign tumors include odontogenic tumors with odontogenic epithelium without ectomesenchyme, odontogenic tumors with odontogenic epithelium with ectomesenchyme, and odontogenic ectomesenchyme with or without odontogenic epithelial rests. Malignant odontogenic tumors are divided into odontogenic carcinoma and sarcoma.



Fig 5-10 Cone-beam volumetric imaging of a 62-year-old male who presented with suspicion of an infected follicular cyst in the left mandible. In the context of cystostomy, tissue was removed for histopathological analysis, which identified a cystic ameloblastoma. The transverse slices revealed lysis of the lingual and crestal aspects of the cortical bone. The course of the inferior alveolar nerve on the lesion floor (arrows) rather than in a canal surrounded by bone must be taken into account when the lesion is surgically removed.

5.3.1 Ameloblastoma

Ameloblastoma is one of the most frequently occurring odontogenic tumors (Figure 5-10). The average age of affected patients is 36 years and the tumor occurs most frequently in the posterior mandible.¹⁰ Radiologically, ameloblastoma appears as a multilocular, sharply demarcated radiolucency (lucencies with “soap bubble” appearance) in 50% of those affected; unilocular variants seem to appear more often in younger patients.¹⁰ The surrounding soft tissues may also be involved as the tumor can expand beyond the buccal, lingual or palatal bone margins. Cystic ameloblastoma is difficult to differentiate radiologically from keratocystic odontogenic tumors and other more frequent cyst forms. In contrast to odontogenic cysts, ameloblastoma should receive radical local treatment. In addition, as in keratocysts, life-time follow-up is recommended based on its tendency to recur.¹⁰

5.3.2 Adenomatoid Odontogenic Tumor

An adenomatoid odontogenic tumor is a slow-growing, expansive lesion in the anterior maxilla or mandible, occurring in children and adolescents (average age 17 years) (Figure 5-11). Both peripheral and central forms (follicular type with tooth and extrafollicular type without tooth) can occur.¹¹ Unilocular translucencies with crowding of the tooth roots are typical findings in the radiological appearance. Punctate opacities in the cyst lumen correspond to calcifications. Follicular and globulomaxillary cysts are two of the most important differential diagnoses. The peripheral form of adenomatoid odontogenic tumor frequently presents as an intraoral swelling. Here, differential diagnoses include fibrous epulis and gingival cyst. The former name for the tumor, adenoameloblastoma, provoked extended resections as it implied that the changes were related to ameloblastoma. In fact, conservative resection is adequate in adenomatoid odontogenic tumor, since no recurrence has been described even in incomplete resections. Therefore, when the follicular type is resected, the affected tooth can remain and be orthodontically corrected, if necessary.

Fig 5-11 Lucency and displacement of 44 with characteristics of a follicular cyst. The histopathological analysis resulted in the diagnosis of an adenomatoid odontogenic tumor. Its location and characteristics suggest that it is a central follicular type.



5.3.3 Odontoma

Odontomas are hamartomas and, like ameloblastomas, are some of the more frequently occurring odontogenic tumors (Figures 5-12 and 5-13). Odontomas contain all components of a tooth: enamel, dentin and cement. They predominantly affect male patients under 20 years of age.¹² Complex and compound odontomas are differentiated. While complex odontomas are encountered more frequently in the mandible and appear radiologically as sharply demarcated, amorphous calcifying masses with lucent borders, compound odontomas occur more often as rather tooth-like structures around a retained tooth in the maxilla. For both types, therapy involves surgical resection and, when possible, orthodontic correction of the retained tooth. Osteoma and cementoblastoma are differential diagnoses to be considered.

5.4 Osteogenic Tumors

5.4.1 Cemento-ossifying Fibroma

Ossifying fibroma is a rare, generally asymptomatic change that predominantly occurs in the premolar and molar region of the mandible (Figures 5-14 and 5-15). In the radiograph, sharply demarcated unilocular roundish-oval lesions with radiopaque elements (calcifications) can be observed.¹³ Juvenile forms occur more frequently in the region of the maxilla, which may result in distensions and facial asymmetries. This must be differentiated from fibrous dysplasia.

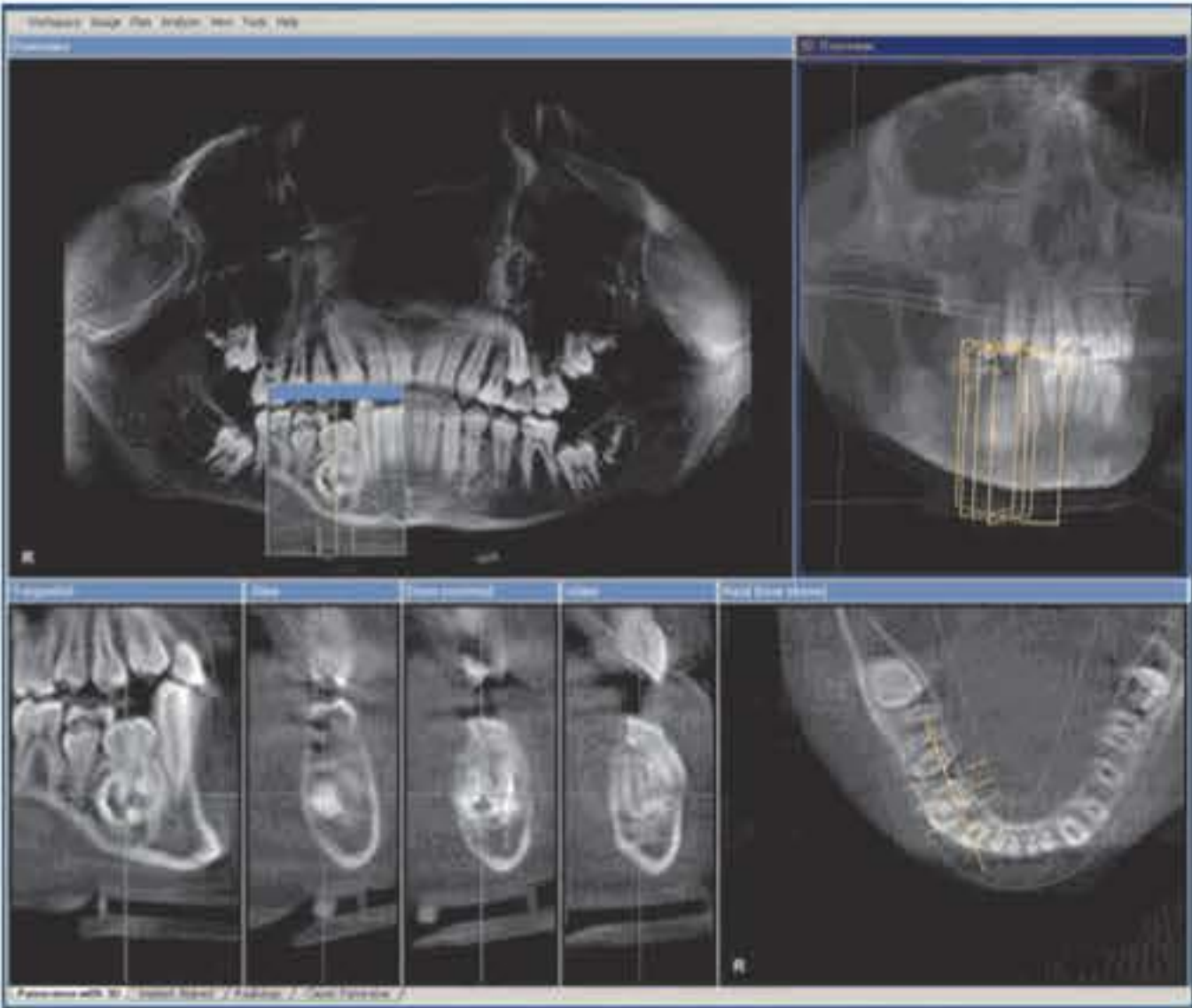


Fig 5-12 Cone-beam volumetric imaging shows a roundish, calcified mass with a lucent border in the mixed dentition of a 10-year-old male. Tooth 44 was vital and was displaced lingually by the complex odontoma.

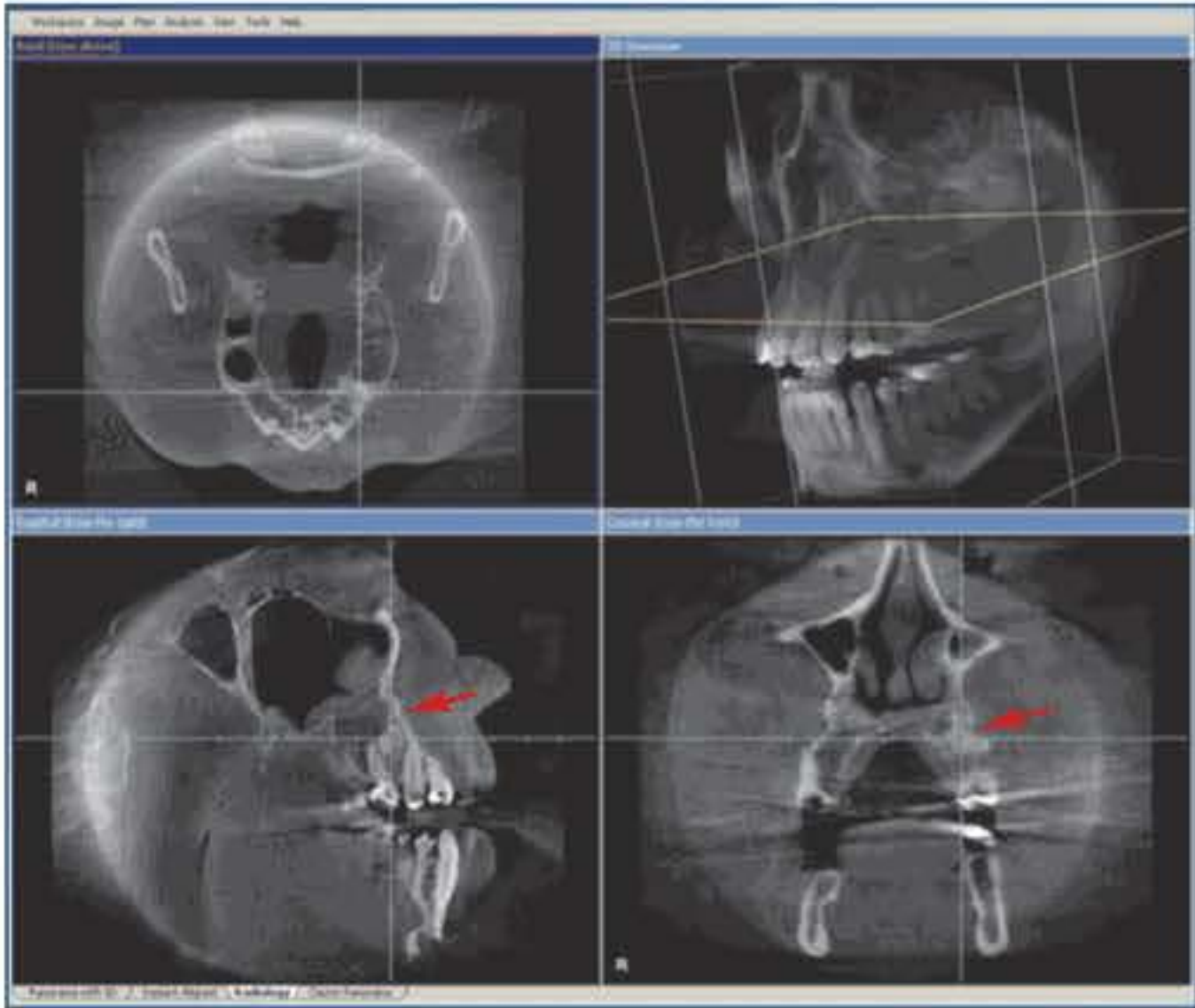


Fig 5-13 Compound odontoma in the left maxilla in the region of 25, in a 36-year-old male, represented as an irregular opacity with a thin border (arrow). Cranially in the sagittal slice, a basal opacity in the maxillary sinus indicates a retention cyst.



Fig 5-14 Ossifying fibroma in the left maxilla of a 15-year-old male. The distension of the maxilla can be seen in the axial and coronal slices. The cystic central lucency is surrounded by a zone of mineralization.

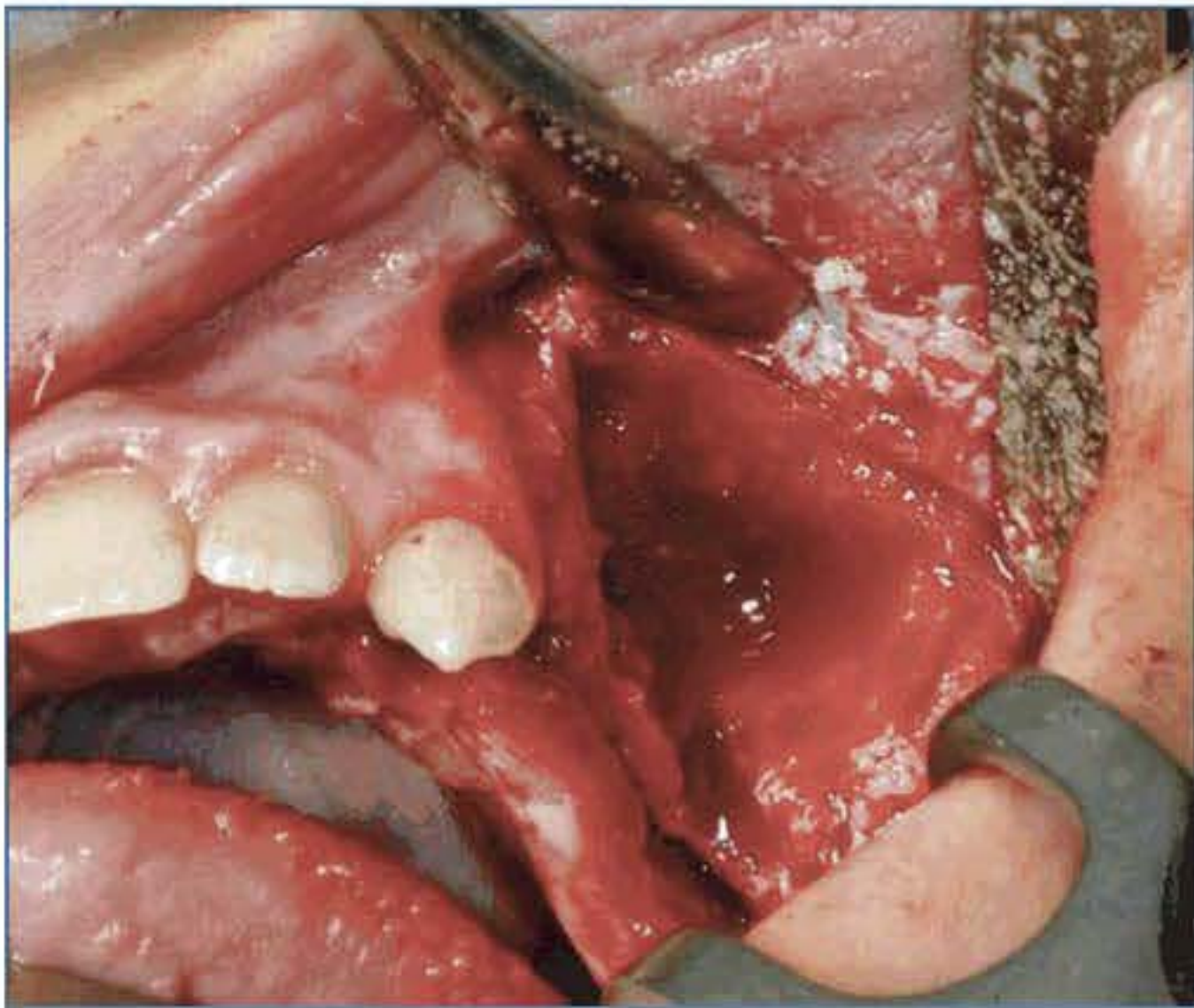


Fig 5-15 Intraoperative view of the patient in Fig 5-14 after excochleation of the ossifying fibroma.

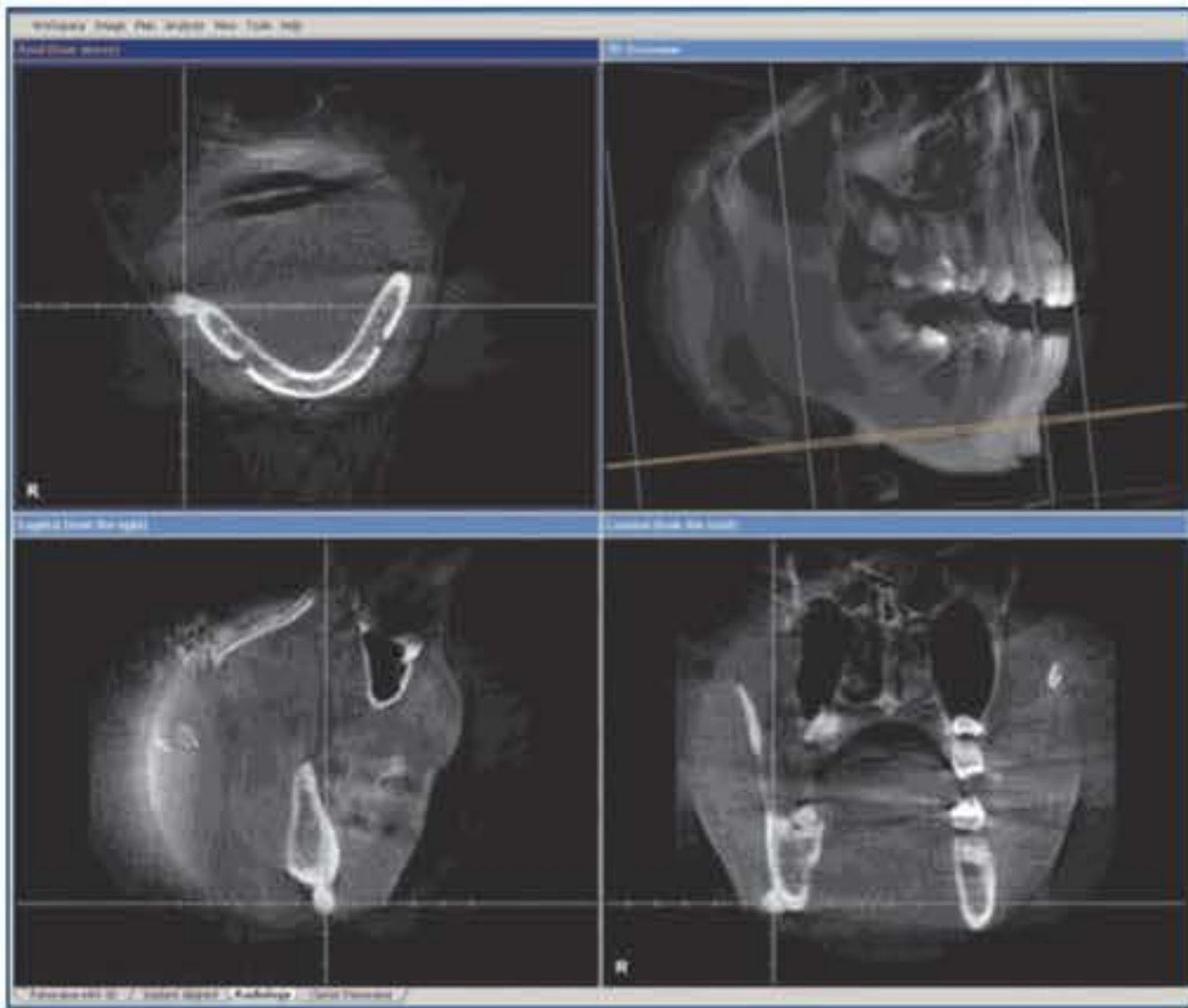


Fig 5-16 The 3D view shows a barely 0.7 mm sized, roundish, bone-dense mass at the lateral basal margin of the right mandible. The histopathological analysis viewed together with the CBVI resulted in the diagnosis of a periosteal osteoma.

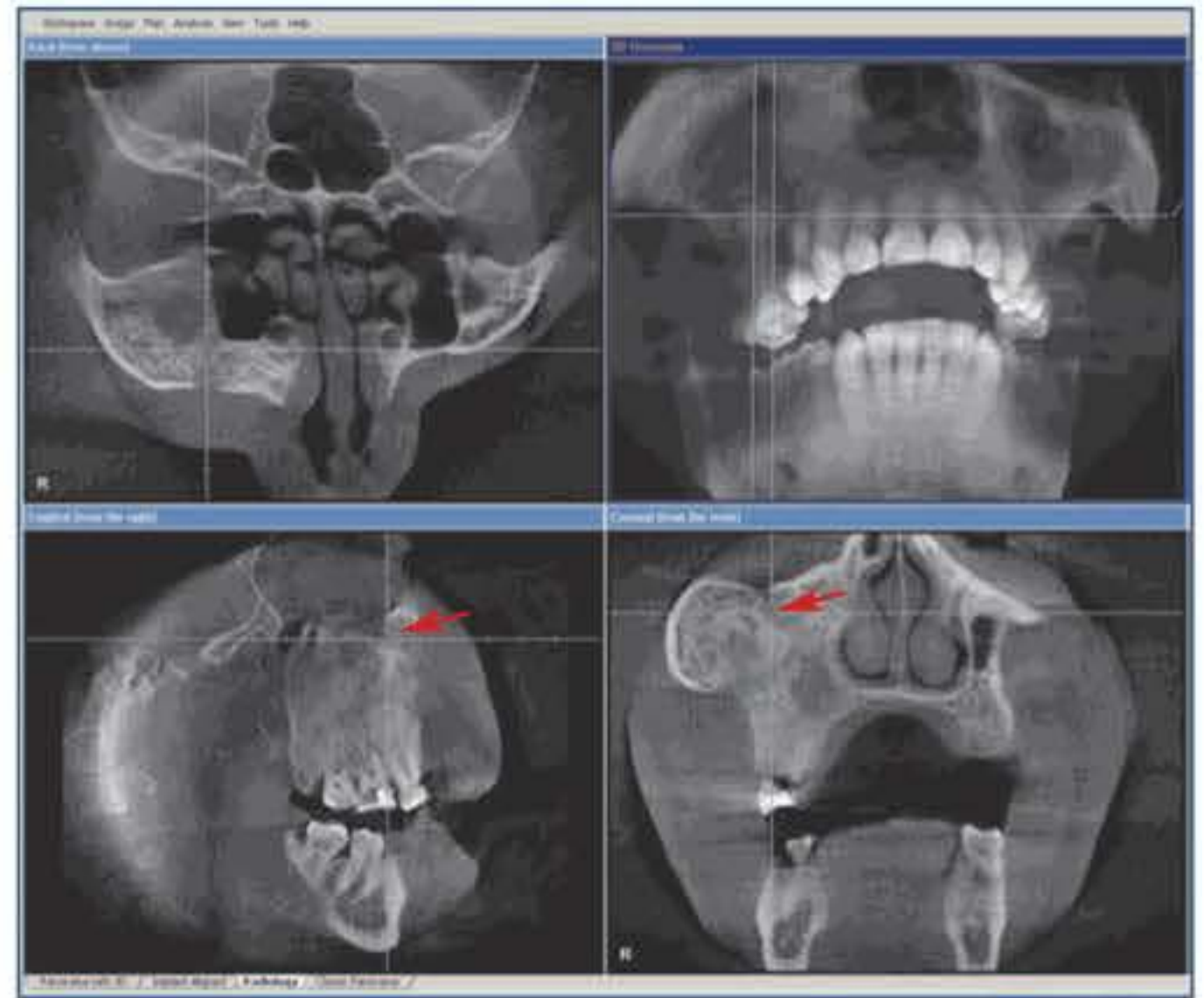


Fig 5-17 Cone-beam volumetric imaging of a 47-year-old male who presented with chronic pain in the right maxilla and slowly increasing distension of the cheek. The right maxilla and the zygomatic bone were distended and have resulted in an enclosure of the infraorbital nerve (arrow) and a reduction of the maxillary sinus. The bone structure shows both punctate osteolysis and zones of increased mineralization, which are more poorly demarcated from the surrounding tissue than in an ossifying fibroma.

5.4.2 Osteoma and Exostosis

Exostoses such as torus palatinus and torus mandibulae are typical findings that normally do not require further investigation. Osteomas can occur both periosteally and endosteally (Figure 5-16). Both are to a great extent asymptomatic and exhibit a compact density in the radiograph. In multiple osteomas, further inquiry with respect to Gardner syndrome is required, because the associated polyps in the large intestine may become carcinomas.

5.5 Non-neoplastic Lesions

5.5.1 Fibrous Dysplasia

Fibrous dysplasia (Figure 5-17) is a hamartomatous pathology characterized by the proliferation of connective tissue (osteolytic stage) and subsequent dysplastic calcification.¹⁴ In principle, any region of the body can be affected. The frequent monosteal form and the rare polyosteal manifestation are differentiated. The maxillary molar region is most frequently affected. Poorly demarcated radiopaque changes with multilocular appearance can be identified radiologically. In agreement with clinical findings, a radiograph often shows an increase in volume of the bony area. The involvement of the infraorbital nerve or the inferior alveolar nerve may trigger pain in a symptomatic trigeminal neuralgia.

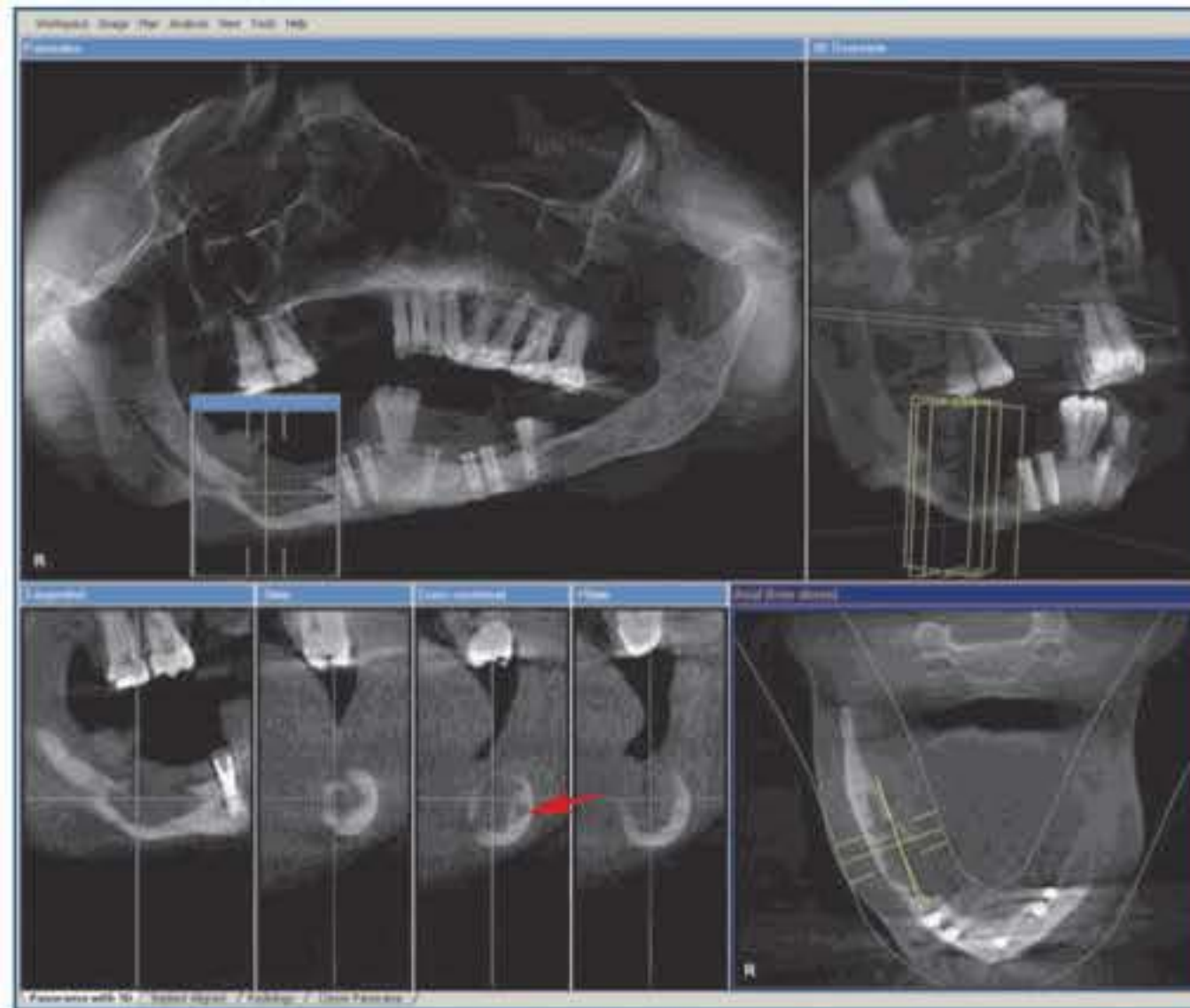


Fig 5-18 Recurrence of a giant cell granuloma in the right mandible of a 32-year-old female patient following multiple resection. Clinically, no abnormalities were identifiable. The osteolysis with loss of the crestal osteon was only demonstrated at radiological follow-up. The displacement of the inferior alveolar nerve can be seen in the transverse slices (arrow).

5.5.2 Central Giant Cell Granuloma

Central giant cell granulomas are non-neoplastic tumors of the tooth-bearing alveolar process, more frequently found in the maxilla than in the mandible, and occurring predominantly in young women (Figure 5-18).¹⁵ While the less-aggressive form appears as smoothly demarcated osteolytic foci with internal septa or trabeculae (honeycomb structure), the more-aggressive forms have pronounced clinical symptoms such as rapid tumor growth, pain, root resorptions and loosening of teeth in addition to the radiological changes.¹⁶

5.6 Malignant Tumors

5.6.1 Osteogenic Sarcoma

Sarcomas are malignant mesenchymal tumors that are prone to hematogenous metastasis and are derived from spindle cells of the osteoid. While osteosarcomas are some of the most common tumors of the skeletal system, only approximately 4% are located in the jaw (Figures 5-19 and 5-20).¹⁷ Osteosarcomas in the jaw region occur 10 to 20 years later than those in the peripheral skeleton, predominantly affect males and have a better prognosis because of the lower rate of remote metastasis.¹⁸ Trauma, fibrous dysplasia and osteitis deformans (Paget's disease) have been identified as predisposing factors.¹⁹ Clinical symptoms can include pain, swelling, paresthesia and anesthesia.¹⁹ In conventional radiography, osteosarcomas appear as mixed osteolytic and osteoblastic, unsharply demarcated masses with periosteal reactions in the form of spicules.



Fig 5-19 Mass lingual of tooth 36 in a 35-year-old male with paresthesia of the inferior alveolar nerve and loosening of teeth 35 and 36.



Fig 5-20 Cone-beam volumetric imaging of the patient in Fig 5-19. In addition to poorly demarcated patchy osteolysis, a washed-out structure of the trabeculae of the spongiosa and lysis of the buccal cortical bone are visible in the axial slice.



Fig 5-21 The CBVI of a 58-year-old male revealed an irregular "moth-eaten" loss of the crestal and lingual cortical bone in the region of teeth 35-38 caused by a secondary carcinoma in the left floor of the mouth. In the axial slice, the inserted implants and the surrounding bone can be seen mainly free of artifacts, in contrast to the view available with conventional CT.

5.6.2 Squamous Cell Carcinoma

Squamous cell carcinoma is the most common malignant epithelial tumor of the oral cavity (Figure 5-21). These tumors primarily occur in the lower part of the oral cavity (tongue, floor of the mouth, mandible). While early, surface-growing tumors may be mistakenly interpreted as prosthesis pressure points or leucoplakia, more advanced, ulcerous changes with an indurated wall and infiltration of the mandible or maxilla are more easily identified. On an x-ray image, the infiltration of the mandible can be identified as an irregular osteolysis with loss of cortical structures.



Fig 5-22 Unclear progressive painless mass in the region of 36 in the left mandible of a 72-year-old male with metastatic plasmocytoma.



Fig 5-23 Cone-beam volumetric imaging of the region in Fig 5-22. Unsharply demarcated osteolyses without sclerotic margins can be identified in the region of teeth 36 and 35. The transverse slices show a thinning of the cortical bone crestally (arrow).

5.6.3 Plasmocytoma

Plasmocytoma (multiple or solitary myeloma) is a malignant pathology in which plasma cells (B lymphocytes) divide uncontrolledly in the bone marrow and produce immunoglobulins (antibodies, generally IgG or IgA) (Figures 5-22 and 5-23). The pathology is associated with susceptibility to infection, anemia, osteolytic lesions and kidney insufficiency.²⁰ With an incidence of 3 in 100,000, plasmocytoma is responsible for 1% of tumor-associated deaths in the Western world. Older persons are more frequently affected, males somewhat more frequently than females.²¹ The etiology of this pathology is unknown; genetic disposition and ionizing radiation are potential candidates.^{18,22} Plasma cell tumors are divided into three subgroups: multiple myeloma, solitary plasmocytoma of the bone and extramedullary plasmocytoma.²⁰ The most frequent symptoms of plasmocytoma in the jaw (in decreasing order) are: swelling, inflamed teeth, impaired nasal breathing, pathological fractures and headaches.²³ The radiograph most frequently identifies osteolyses, which can appear as multilocular soap-bubble lesions, as lucencies with a cystic appearance or as destructive bone resorptions.²³

5.7 Avascular Bone Necrosis following Bisphosphonate Therapy

In recent years, an increase in the rate of infected osteonecroses both in the maxilla and in the mandible has been noted in patients with tumors (Figures 5-24 to 5-27). In a series of studies, the administration of bisphosphonates for the treatment of bone metastases has been assumed to be the cause.^{24,25} Although a causal relationship between bisphosphonate therapy and the occurrence of osteonecrosis has not yet been conclusively established, this possible adverse effect has



Fig 5-24 Clinical picture of a 45-year-old female with metastasized breast cancer and bisphosphonate therapy for bone metastases and after tooth extraction in the left maxilla. She presented for specialist care for pain and increasing putrid exudate from mouth and nose. The left part of the affected maxilla is clinically mobile.

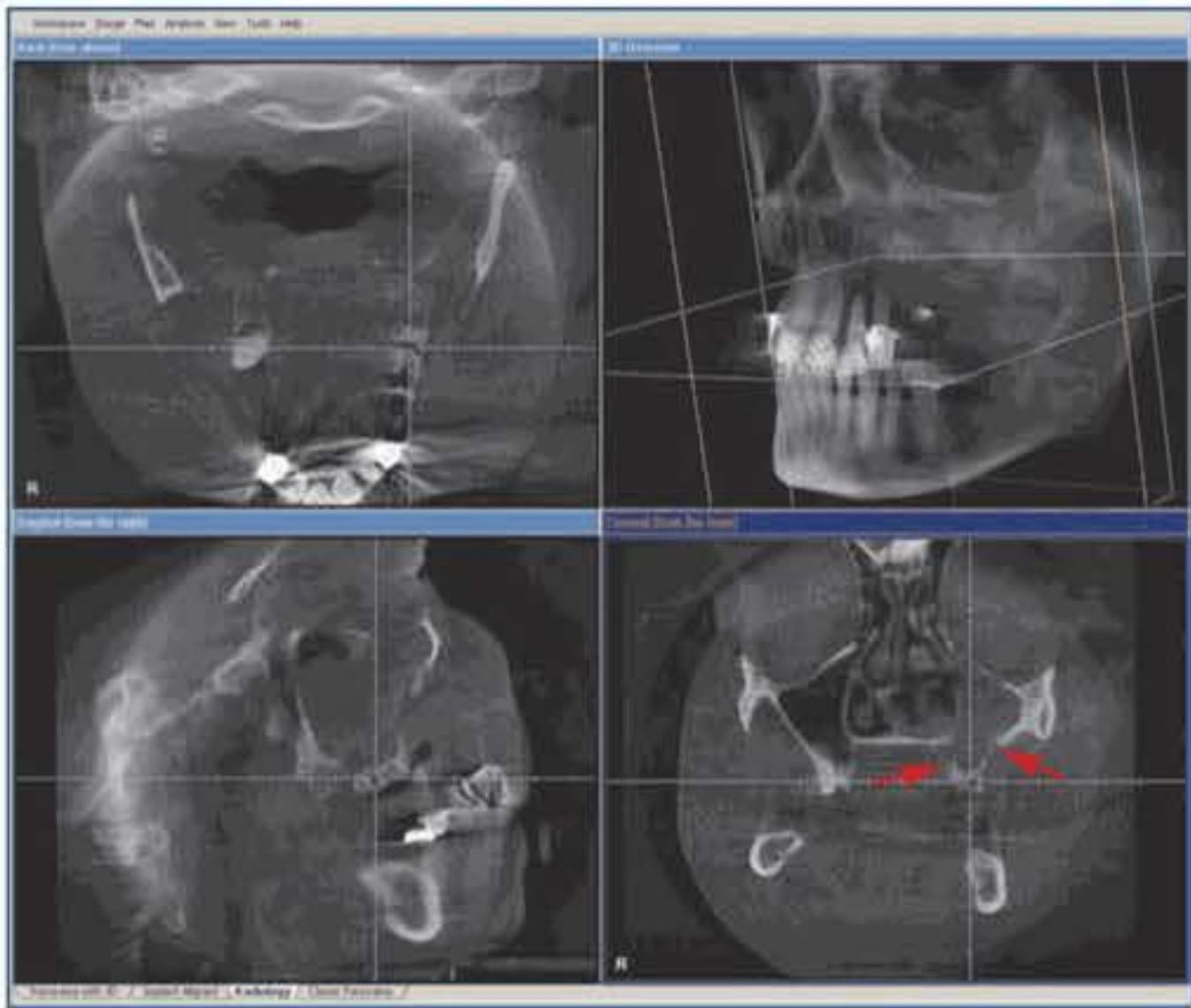


Fig 5-25 The coronal slice of the CBVI of the patient in Fig 5-24 revealed a disintegration of the cortical structures and a washed-out structure in the left maxilla. Missing bony connections to the hard palate and the zygomatic bone indicate the already clinically recognizable sequestration of the left maxilla (arrows). In the sagittal slice, the left maxillary sinus only exhibits a ventilated residual lumen craniodorsally. Soft tissue swelling in the left nasal floor can be seen in the coronal slice.



Fig 5-26 A 64-year-old patient with a metastatic colon carcinoma who was treated with bisphosphonates and radiation therapy for multiple bone metastases. CBVI was carried out because of therapy-refractory pain and hypesthesia of the right inferior alveolar nerve. In the panoramic view, osteolysis measuring 10 mm can be identified in the region of tooth 48. Compared with the left mandibular angle, the surrounding bone in the right mandibular angle exhibits an "enostosis-like" appearance, displaying enhanced densification and mineralization of the spongiosa structures. The alveolar nerve canal is well demarcated in the transverse slice (arrows).



Fig 5-27 Bone scintigram of the patient in Fig 5-26, which documents the activity in the right mandibular angle and shows multiple spots of increased bone turnover indicating bone metastases in ribs, thoracic spine, humerus and femur.

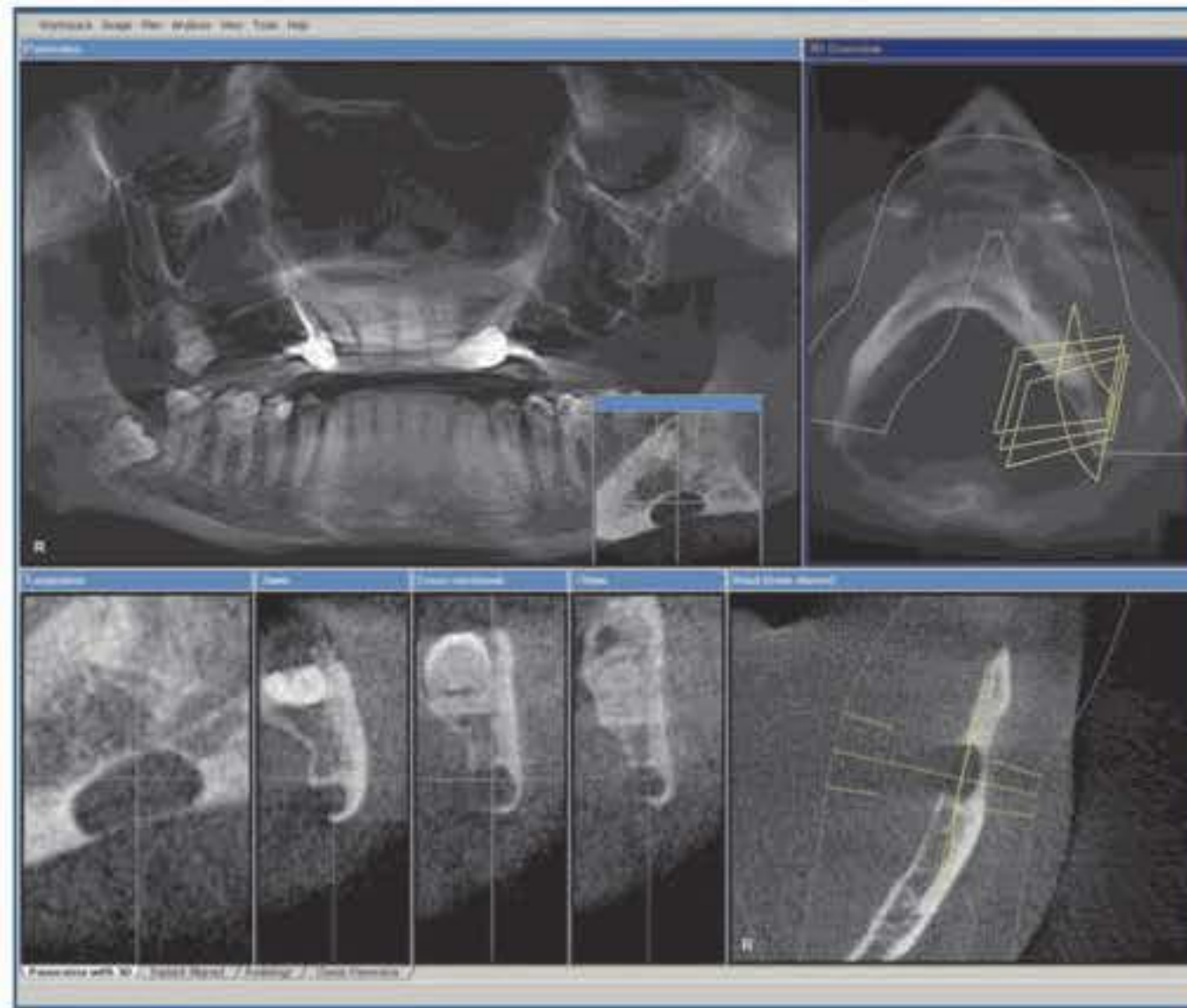


Fig 5-28 *Incidental finding of a Stafne bone cavity in the left mandible during CBVI for 3D implant planning. Sharp demarcation of the bone margin due to pressure resorption without pathological findings.*

been included in the instructions on use of pamidronic acid and zoledronic acid. Bisphosphonates are primarily used in tumor-induced hypercalcemia resulting from osteolytic bone metastases of breast cancer, plasmocytoma and Paget's disease. Bisphosphonate inhibits the osteoclasts required for bone breakdown and remodeling. Because bisphosphonates have a long half-life of several years in bone, infections may be delayed.²⁴ Clinically, symptoms frequently occur only after den-toalveolar procedures such as tooth extraction, since the empty alveolus permits a bacterial colo-nization of the necrotic bone area, with extensive putrid infection. Radiologically, the affected area is recognized by increased sclerosis of the spongiosa; sequestra are less common than in osteomyelitis. In contrast with infected osteoradionecrosis, which primarily manifests in the mandible, the maxilla appears to be affected almost as frequently as the mandible following bis-phosphonate therapy.²⁶

5.8 Pseudocysts of the Jaw

Cystic, oval changes are occasional incidental findings in the mandibular posterior dentition, predominantly located inferior to the mandibular canal. These are called lingual or buccal mandibular cavities (Stafne bone cavity) and should not be interpreted as pathological and requiring treatment. The Stafne bone cavity is formed as a type of bone resorption (bone inden-tation) in the area of the submandibular gland, induced by a constant pressure on this bone area in the dorsal mandible. The lingually situated Stafne bone cavity can be easily visualized using CBVI (Figure 5-28).

5.9 Summary

The investigation and therapy planning for cystic changes in the maxilla and mandible require good radiodiagnostics. While smaller cystic changes (< 2 cm) can in most cases be investigated using conventional radiodiagnostics (OPG, dental film and occlusal radiograph), advanced tomographic diagnostics (CT or CBVI) are indicated for extensive changes in the jaw. Conventional images, such as cranial PA (occipitofrontal projection) according to Clementschitsch, and paranasal sinus images can very rarely demonstrate the cystic lesion and the relevant adjacent structures such as the inferior alveolar nerve and the nasal and maxillary sinus floor without superimpositioning. In contrast with dental CT, CBVI permits the individual selection of planes, meeting the demand for dynamic multiplanar imaging without distortions. In particular, the course of the inferior alveolar nerve relative to the cyst and remaining wisdom teeth can be visualized with sufficient accuracy for planning mandibular cyst surgery. This procedure is also suitable for examinations of bone regeneration following cystectomy because volumetric measurement of the cyst lumen can be performed, if necessary. The lack of sharpness of the image in the region of the maxillary and mandibular front teeth in conventional OPGs can be compensated for in CBVI by subsequent correction of the panoramic slice, thus eliminating the complementary second plane that occurs in a mandibular occlusal radiograph. This is particularly useful when assessing radicular cysts in the region of the mandibular front teeth.

From a practical point of view, the panoramic view with the examination window and the transverse slices is more suitable for assessing mandibular lesions, while cysts of the maxilla are better demonstrated in the axial, coronal and transverse slices. This also applies to odontogenic and osteogenic tumors of the jaw. Compared with OPG and dental film, the resolution is slightly reduced in CBVI when assessing intraosseal changes; however, this is entirely compensated by the 3D presentation of the topography. In tumors that expand beyond the lingual or buccal cortical bone into the surrounding soft tissues, a CT examination (soft tissue window) should follow in some cases, especially if malignancy is suspected. The evaluation of inflammatory bone changes is considerably facilitated by 3D CBVI because the bone structure can be evaluated in 3D for sequestration, as well as for possible entry portals in the form of root remnants or apical granulomas. In terms of radiation dosage, the preparation of one CBVI is significantly more advantageous than imaging using several conventional images or one conventional CT.^{27–29} Cone-beam technology is less susceptible than conventional CT to image artifacts caused by metallic restorations, implants or osteosynthesis materials because of the geometry of the x-ray beam and the image computation algorithm.²⁷

5.10 References

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6 Periodontal Diseases

Esther Lowden

Periodontal diseases are clinically diagnosable. During the visual intraoral examination, pathological changes are revealed by inflammation of the gingiva and recessions. The measurement of the gingival sulcus reveals increased periodontal probing depths, bleeding and suppuration upon probing. However, a precise clinical estimation of the loss of supporting bone is not possible. In estimating the progression of periodontal disease, radiological diagnostics are an essential aid to making a specific diagnosis and planning treatment (Figure 6-1).¹ Exceptions are initial periodontal lesions, since osteolytic changes can only be visualized in a radiograph after a 30 to 50% reduction of the bone mineral.² The planning of periodontal surgery and the prognosis of achievable treatment are largely based on radiographic diagnostics. During supportive periodontal treatment, it is essential to compare images to verify risk sites. The aspects of periodontal diseases that can be addressed by radiological diagnostics are presented here in the context of the current classification.³

6.1 Gingivitis

The radiological exclusion of the loss of supporting bone confirms the diagnosis of gingivitis. The alveolar crest is located 2 to 3 mm apical of the cemento-enamel junction.⁴

6.2 Periodontitis

When classifying periodontal diseases, periodontitis is categorized according to its form of progression and etiopathogenesis. Radiological diagnostics may support differential diagnostics but can only hint at a specific form of progression. In periodontal radiological diagnostics, it is recommended that the following are examined.

1. Anatomy of the alveolar crest
 - horizontal bone loss
 - vertical bone loss
 - furcation involvement
2. Width of the periodontal space
3. Calculus.



Fig 6-1 A 56-year-old male with localized severe aggressive periodontitis.



Fig 6-2 Advanced horizontal bone loss with furcation involvement at tooth 18. A class II furcation involvement (distal) is suspected.

6.2.1 Chronic Periodontitis

In chronic periodontitis, horizontal bone loss predominates. Depending on the severity of bone loss and the morphology of the tooth, furcation involvement may also occur (Figure 6-2). An enlarged periodontium may be another indication of pathological changes. Radiologically visible calculus frequently occurs in this type of periodontitis.

6.2.2 Aggressive Periodontitis

Vertical intrabony defects are typical radiological manifestations of aggressive periodontitis (Figure 6-3). The alveolar crest shows an irregular outline. Furcation involvement is defined less by horizontal bone loss than by the bizarre shape of the vertical intrabony defect itself. An enlarged periodontal space is a sign of a pathology here as well. There tends to be a lack of radiologically visible calculus with this type of periodontitis.

6.3 Periodontitis as a Manifestation of Systemic Disease

Where periodontitis is associated with systemic disease, medical history and clinical features are most important for diagnosis. Radiologically, the periodontitis can be assessed as chronic or aggressive.



Fig 6-3 Vertical bone defect at the distal side of tooth 38. The intraosseous pocket also reveals class II furcation involvement from a lingual direction as well as a complex configuration that is primarily single walled in nature.

6.4 Necrotizing Periodontitis

Necrotizing periodontitis has a typical clinical appearance that can be confirmed by radiology depending on its severity. Advanced bone loss, primarily in the approximal area, is characteristic of this form of disease. In differential diagnostics, it is difficult to distinguish from aggressive periodontitis using radiography.

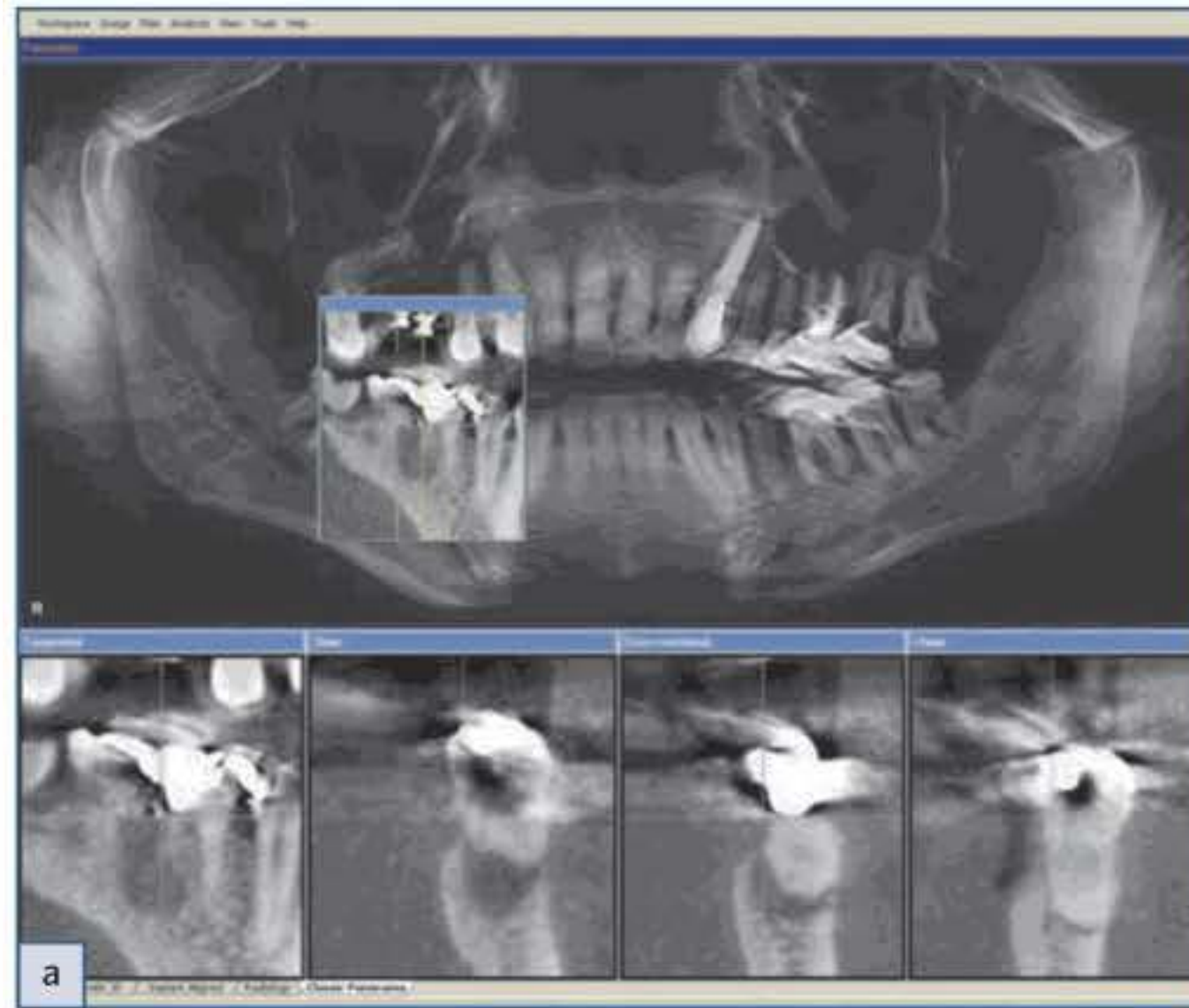
6.5 Periodontal Abscess

In addition to the clinical findings, periodontal abscess manifests radiologically as a loss of attachment. If the abscess affects the molar area, furcation involvement usually exists.

6.6 Periodontal–Endodontal Lesions

If the radiograph reveals advanced bone loss extending to the apex, a periodontal–endodontal lesion may exist (Figure 6-4). Radiological diagnostics are only helpful in determining the etiology of the pathological event by documenting the progress of the disease. Advanced localized periodontal lesions can cause endodontic problems,⁵ but they may not.⁶ Radiological diagnostics cannot determine whether there is a pathological involvement of the pulp.

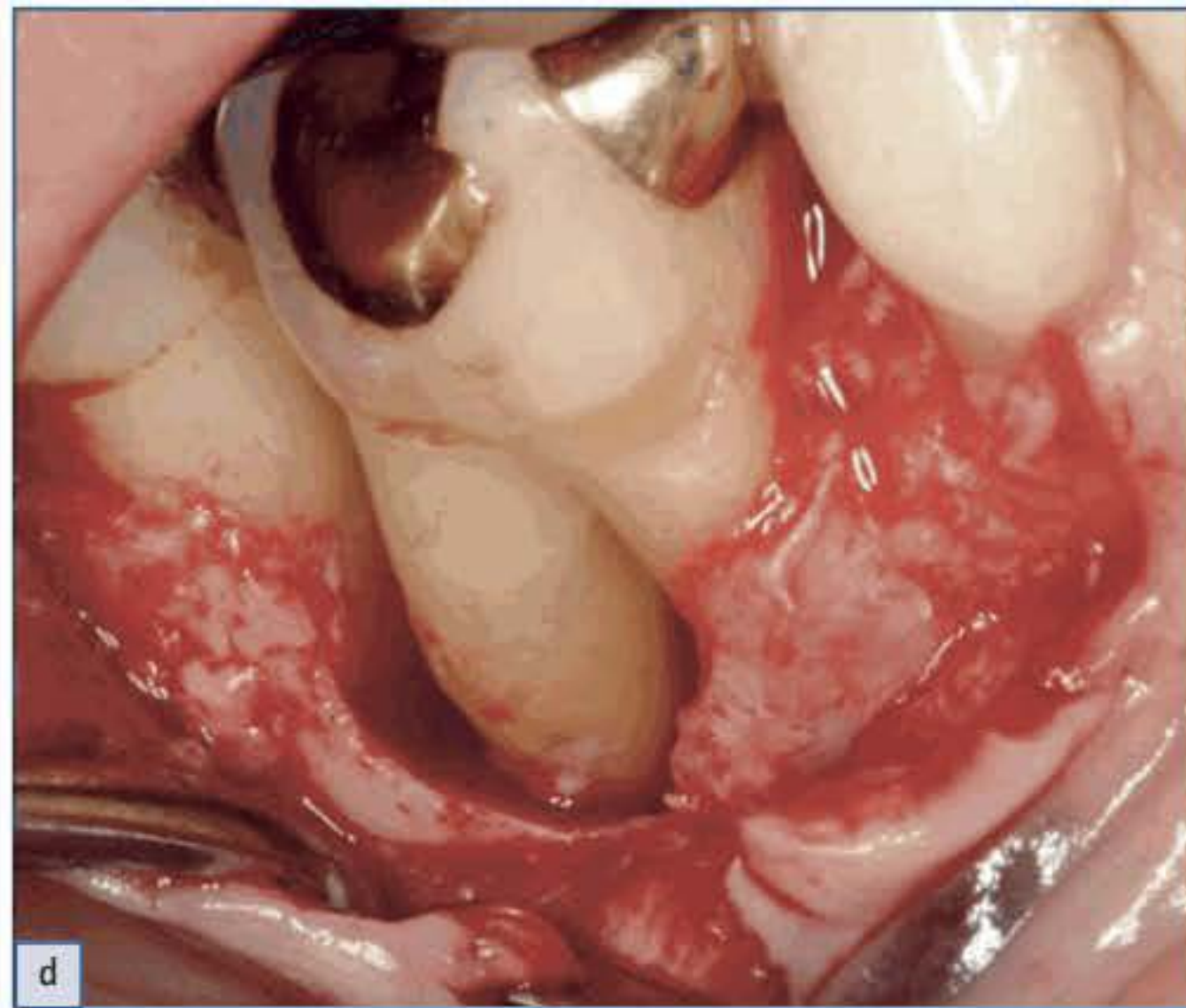
Fig 6-4 Combined endodontal–periodontal defect of the distal root of tooth 46. The distal, vertical intra-bony defect extends into the apical root region. (a) Vestibular view; (b) central view; (c) lingual view; (d) clinical situation; (e) visualization of further details.



6.7 Developmental or Acquired Deformations and Conditions

Radiography can be used to identify deviations in tooth anatomy, insufficient margins of crowns and fillings, root fractures, root resorption and enamel and cement pearls. Mucogingival disorders and changes in the mucosa can only be evaluated clinically. In occlusal trauma, radiological diagnostics can be of decisive assistance. If there is an unusual, uneven widening of the periodontal space, a clinical check for the presence of occlusal trauma is indicated. In periodontitis, occlusal trauma hastens the loss of the osseous attachment of the tooth. A periodontal–endodontal lesion may arise.

Fig 6-4 (d, e).



6.8 Diagnostic Value of Cone-beam Volumetric Imaging

Numerous studies have shown that limited information can be acquired from full-mouth radiographs for periodontal diagnostics. Radiographs of teeth are flat projections of complex 3D anatomical structures. Osseous defects can be overlapped by intact compacta or roots, whereas thin bone lamella can be overexposed through incorrect projection direction or excessive irradiation.¹ Compared with the clinical situation during surgery, bone loss is underestimated and overlooked at some locations.⁷ Only in 43.7% of patients do radiological and clinical evaluations agree in the identification of furcation involvement.⁸ Dehiscence and fenestration of the oral and vestibular surfaces of teeth are particularly difficult to evaluate.⁹ The morphology and the size of

intraosseous defects cannot be properly assessed.⁸ Only in 50% of patients is calculus successfully detected on interdental root surfaces.¹⁰

CBVI assists in evaluating and analyzing the 3D periodontal situation. Intraosseous defects with one, two or three walls can be distinguished, and furcation involvement can be classified. Radiological diagnostics are more likely to correspond closely with the clinical situation for horizontal and vertical bone loss. Unusual features are more readily identified and localized by radiology and it is most likely to estimate the real dimensions of the defects more precisely prior to the surgical procedure. Initial clinical results support these predictions.

6.9 References

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7 Caries

Rainer Haak

7.1 Background

The prevalence of caries in industrialized countries has been reducing over recent decades and its incidence distribution has changed.¹ The greatest increase in the frequency of caries has been among children and adolescents.² Primary lesions tend to arise on occlusal surfaces, and approximal lesions increasingly appear after age 12. This development is reflected in the changed appearance of carious lesions. Initial lesions that have not yet penetrated the surface greatly outnumber established defects or filled tooth surfaces,³ which makes it substantially more difficult to detect and classify carious lesions (Figures 7-1 and 7-2).⁴

Fig 7-1 Occlusal surface with discoloration mesial to the transverse crest. A subtle opacity is visually perceptible that is easy to overlook under clinical conditions.



Fig 7-2 The histology revealed unambiguous carious demineralization that had already reached the enamel-dentin interface.



7.2 Diagnostic and Therapeutic Strategy

Therapeutic approaches have changed to reflect these population changes. Where restorative therapy used to be the only treatment option when a carious lesion was discovered, now it is clear that controlling the bacterial biomass is the preferred therapeutic option for treating caries. Only if this biofilm directly contacts the dentin can a significant bacterial invasion occur. Contrary to widespread opinion, carious changes in the dentin per se, which are known to arise much earlier, are not a suitable indication for pursuing invasive therapy.⁵

This has different implications for occlusal versus approximal carious lesions. Whereas an evident dentin involvement represents the threshold for invasive therapy for occlusal lesions, based on the morphology, the thinner enamel in the fissure fundus and the moderate caries protection offered by preventative strategies (e.g. fluoride and chlorhexidine),⁶ the penetration of the enamel-dentin junction does not justify a filling in approximal lesions.⁷ The quality of the tooth surface is currently considered to be the determining factor in the restoration decision, since it is one of the key issues affecting the ability to maintain hygiene and remove the cariogenic biofilm. Once cavitation exists, the entire metabolism of the biofilm changes.⁸

Since a clinical appraisal is insufficient for occlusal and approximal areas, various diagnostic techniques are recommended. Fissures and pits are best examined by laser fluorescence (DIAGNOdent, KaVo, Biberach) or bitewing radiography. An additional technique useful for approximal areas is fiber-optic transillumination.^{9,10} However, none of these techniques deals directly with the morphology of the tooth surface as they all estimate the potential depth of carious demineralization. Since the correlation between the detectable demineralization front and surface appearance is not exact,¹¹ an option is still being sought that can disclose this essential diagnostic information for visually inaccessible tooth surfaces.

Radiological 3D tomographic techniques could be particularly suitable in this area: the summation effect characteristic of intraoral radiographs, where relevant information is superimposed by structures in the beam path, does not occur and the location of the section can be freely chosen from a 3D volumetric data set. Therefore, the examiner is not restricted to the bucco-oral projection and the associated display of conventional radiographs. Recent experimental studies have shown that dental hard substance can be evaluated using local tomographs¹² and that caries detection may also be improved¹³ (Figures 7-3 to 7-6).

Against this background, our working group has addressed the question of whether cavitations of approximal carious lesions are more easily detectable by CBVI than with conventional bitewing radiography. CBVI achieved 80% sensitivity and 96% specificity for detection of approximal carious cavitations, whereas only 29% were correctly identified using bitewing radiography (Figures 7-7 to 7-9).⁴

These highly promising results indicate that cone-beam technology might be useful in distinguishing between intact and cavitated tooth surfaces in the approximal area. Individual case studies have indicated that the technology is also better for identifying occlusal dentin lesions than is conventional radiography (Figure 7-9). Publications in preparation on this topic are awaited with interest.



Fig 7-3 Conventional orthopantomograph of a 31-year-old female. Coronal radiolucencies indicating carious lesions are difficult to discern. At tooth 27, a distal translucency is visible that appears to indicate a pronounced carious lesion.



Fig 7-4 Clinically, the approximal space between 27 and 28 appears unremarkable upon visual inspection.

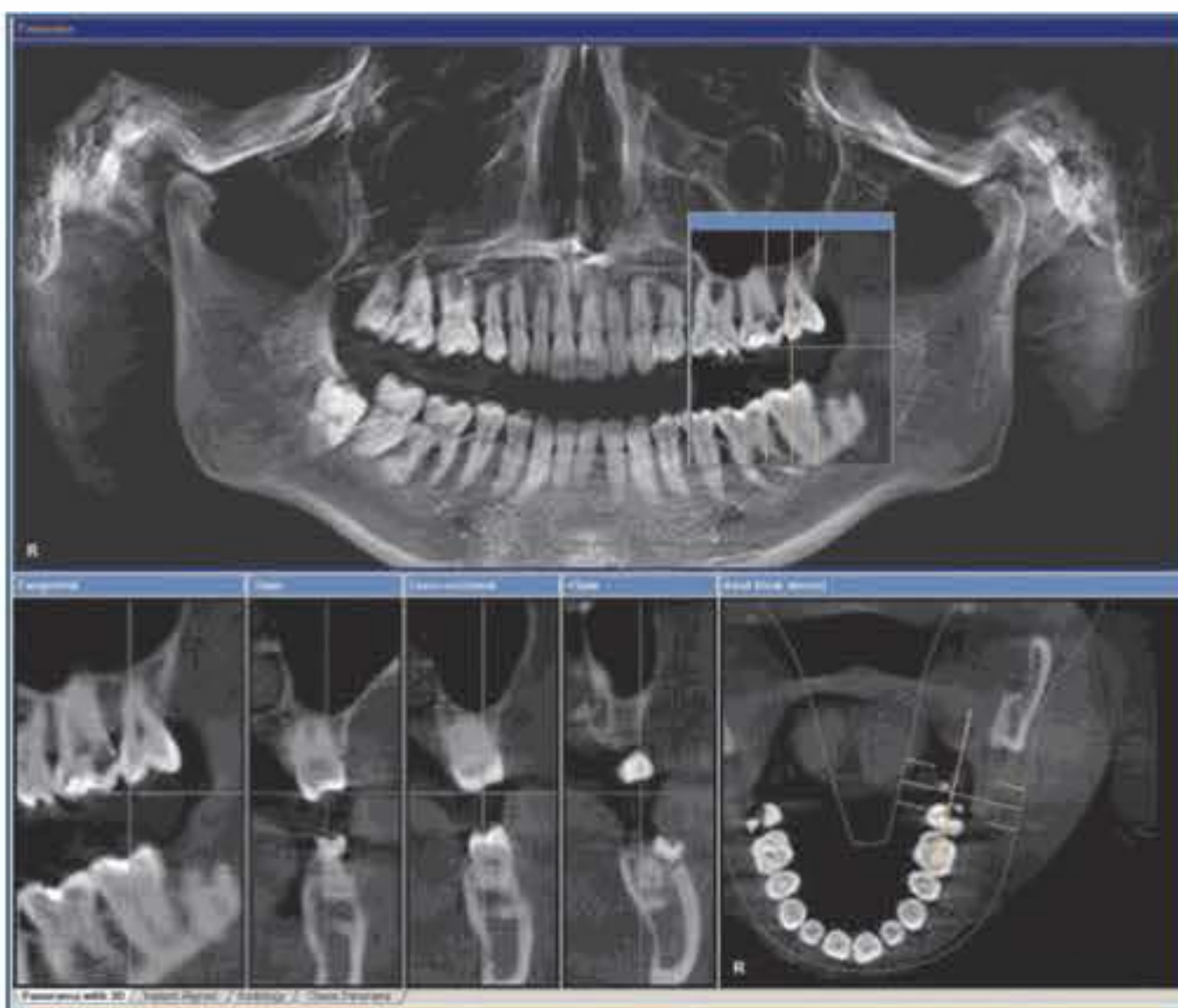


Fig 7-5 The extent of the radiological translucency of tooth 27 is evident in the panoramic view of the CBCT of the patient in Fig 7-3. In the tangential view, the tooth surface discontinuity can be seen at the bottom left. In addition, the carious lesion probably extends in depth to involve direct pulp contact.

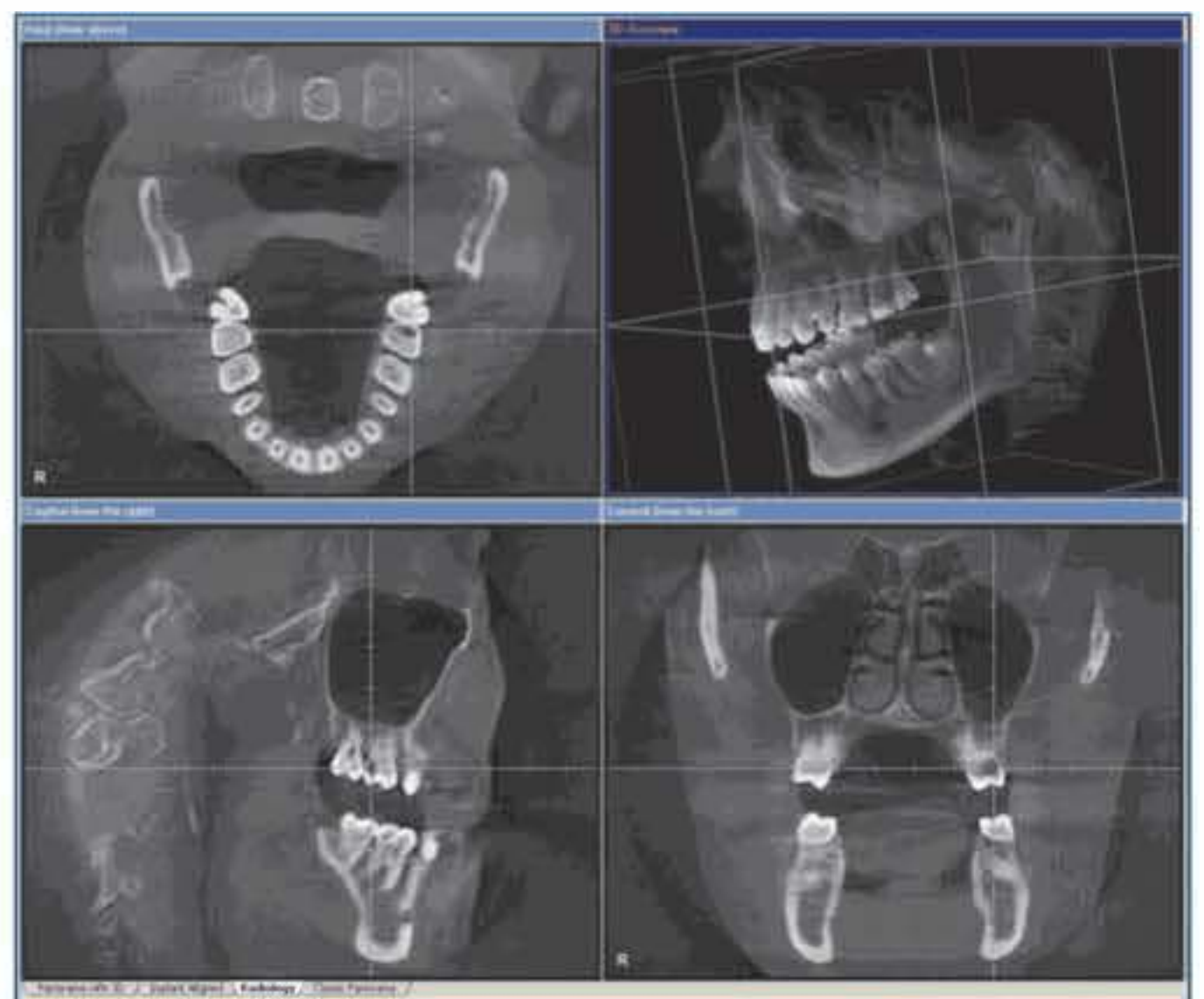


Fig 7-6 In other tomographs from the GALILEOS system, the carious lesion of tooth 27 is also clearly identifiable, and its 3D extent can be evaluated.



Fig 7-7 In the digital intraoral image (Sidexis, Sirona, Bensheim), the radiolucencies of carious lesions involving dentin are evident at the distal side of tooth 15, the mesial side of tooth 16 and distal side of tooth 46. It is difficult to evaluate the status of the approximal surfaces, so the examiner is forced to focus primarily on the depth of the lesions and can only indirectly assess the existence of a cavity.

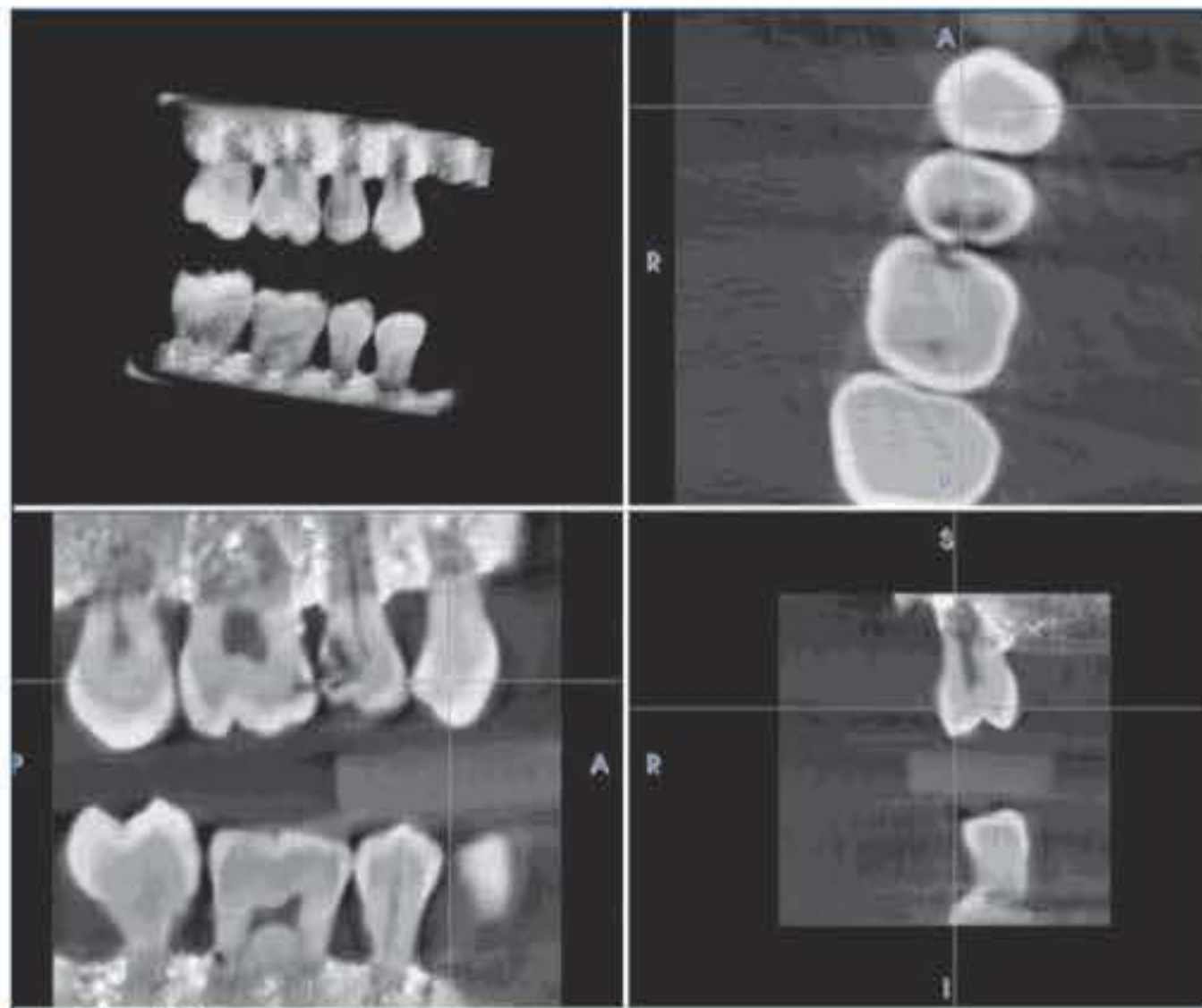


Fig 7-8 Compared with digital intraoral radiography, the radiolucencies of the carious lesions in teeth 15 and 16 as well as tooth surface discontinuities are clearly discernible in the slice image produced by CBVI.

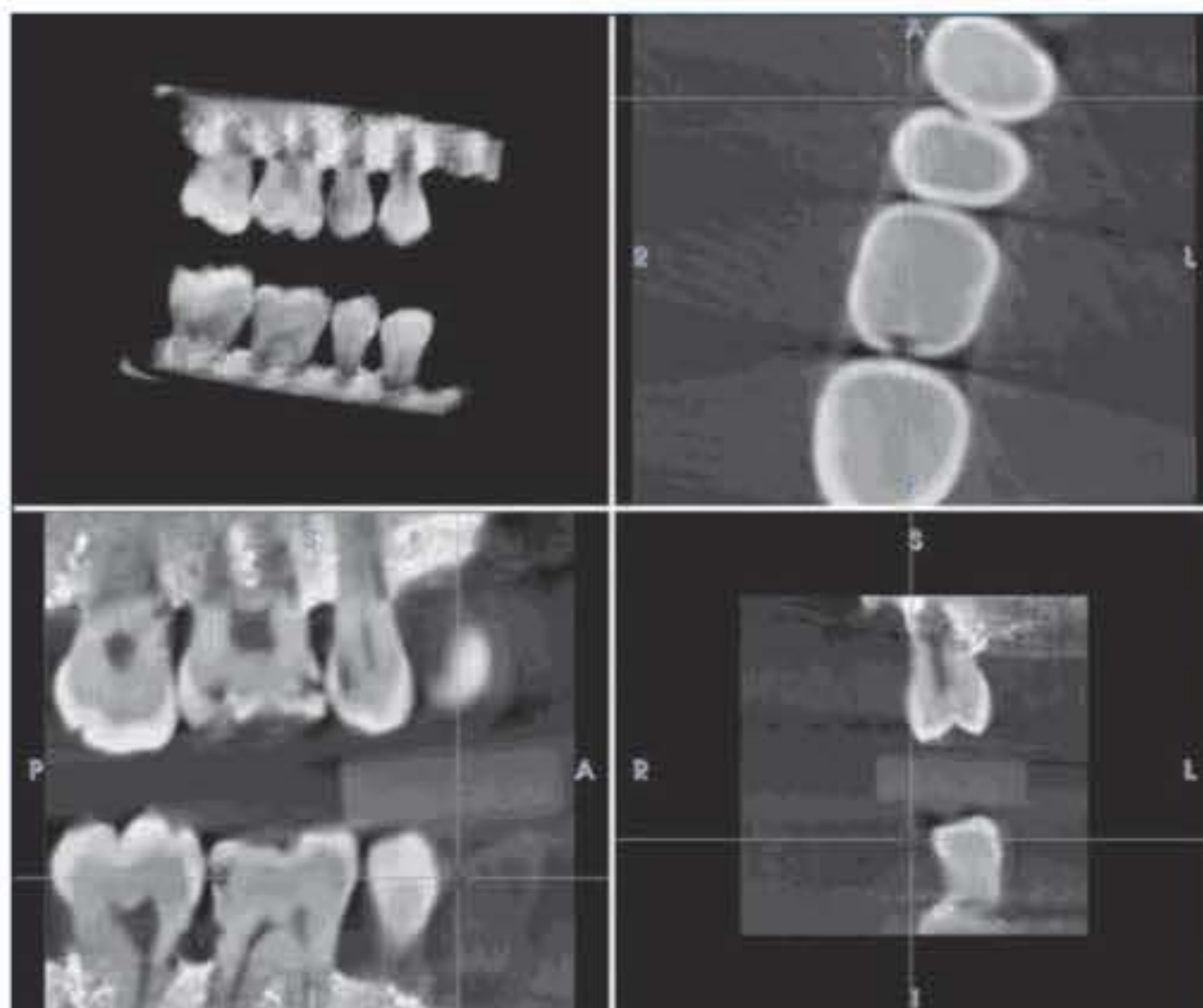


Fig 7-9 The status of the distal approximal surface of tooth 46 can also be clearly diagnosed with CBVI, enabling a therapy to be chosen with greater confidence than on the basis of conventional bitewing radiography. In addition, a significant dentin lesion is apparent in the maxilla at tooth 16, which could only be suspected from conventional imaging techniques and would most likely be overlooked.

7.3 References

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8 Orthodontic Diagnostics

Bert Braumann and Mitra Saffar

Deviations in the orofacial system can involve dentoalveolar malpositions, skeletal deviations in the sagittal, vertical and transverse directions, as well as functional deviations. In addition to endogenous factors such as genetic variation, exogenous factors (e.g. environmental factors such as dysfunctions, trauma, tooth loss or iatrogenic influences) are also responsible for malocclusions, and functional influences will also contribute. This phenomenon is described as a multifactorial cause with a threshold.¹

A comprehensive differential diagnosis is, therefore, essential in orthodontics. Today, such a diagnosis is achieved using a variety of techniques to analyze morphological and functional deviations within the orofacial system. These include patient interview, an initial examination of the patient, the general and specific medical history, clinical findings of the facial soft tissue, an examination of the orofacial region, examination of the intraoral hard and soft tissues, a comprehensive model, and photographic and x-ray analyses.

After an evaluation of all the clinically relevant individual findings, an overall precise and comprehensive orthodontic diagnosis is determined to guide therapy for the specific problem and its causes.

8.1 Orthodontic Radiological Diagnostics

The orthodontic radiological examination is usually based on two different techniques, the panoramic tomograph and the lateral cephalograph.

Evaluation of the dentition and the structures of the facial skull includes the determination of the tooth status, the developmental stage of the teeth and their shape and position in the jaw. Particular emphasis is placed on potential eruption disturbances. In addition, pathological changes can be identified in the teeth, their roots, the jaw, the two temporomandibular joints, the accessory nasal sinuses (paranasal sinuses) and the eye sockets. Of course, general dental findings such as conservative or prosthetic restorations and the status of the periodontium are also evaluated.¹

The lateral cephalograph enables a precise depiction of all bony structures of the neurocranium and visceral cranium and, when certain filters are used, of the facial soft tissue. Conclusions can be drawn about the size and shape of the jaws, their position in sagittal and vertical relation to the anterior base of the skull, and their position relative to each other. In addition, the lateral cephalograph provides information on the axial inclination of the anterior and posterior teeth in the sagittal direction, the extent of the surrounding alveolar bone and the relationship of the anterior teeth to the facial soft tissue.²

Cephalometric radiographs aid in determining the sagittal position of the maxilla and mandible in the skull, their relative orientation, and dental and soft tissue parameters.³ An analytical method is used to identify and analyze the necessary parameters. It involves determining hard tissue and soft tissue landmarks and making angular and linear measurements. Potential sources of error must be considered when using the determined values. They include the difficulty in locating some reference points. Nevertheless, a cephalometric analysis is an essential component of orthodontic diagnostics.

8.2 Dentoalveolar Malpositioning

Dental malpositioning affects 60 to 70% of all children and adolescents.⁴ Dentoalveolar malpositioning includes both deviations of individual teeth as well as maldevelopments in the alveolar process region. Anomalies in the number and shape of teeth as well as eruption disturbances and displacement of individual teeth are discussed in Chapters 3 and 4.

8.2.1 Lingual/Palatinal Position

The 3D localization of erupted and non-erupted teeth plays a major role in planning orthodontic treatment.

In addition to the vertical evaluation described in Chapter 4, teeth can be evaluated in the mesiodistal and buccolingual directions with the aid of 3D imaging. This permits an assessment of the required space in the dental arches (Figure 8-1). Previously, this could only be done using CT images.



Fig 8-1 An 8-year-old boy with cleft lip and palate. The 3D image confirms the delayed exfoliation with the prospective lack of space for lingually erupting teeth 32 and 42. The primary crowding in the anterior region indicates a malrelation between tooth and jaw size.



Fig 8-2 A 12-year-old boy in ongoing orthodontic treatment. (a) The intermediate diagnostic of the panoramic view shows no pathological findings, and no dento-alveolar malpositioning is diagnosed, particularly in the anterior region. (b) Closer inspection of the 3D image does not support the clinically unremarkable anterior mandibular tooth position. The axial view reveals the apically increasing mesial rotation of the root of tooth 41, where a relapse is likely to occur.

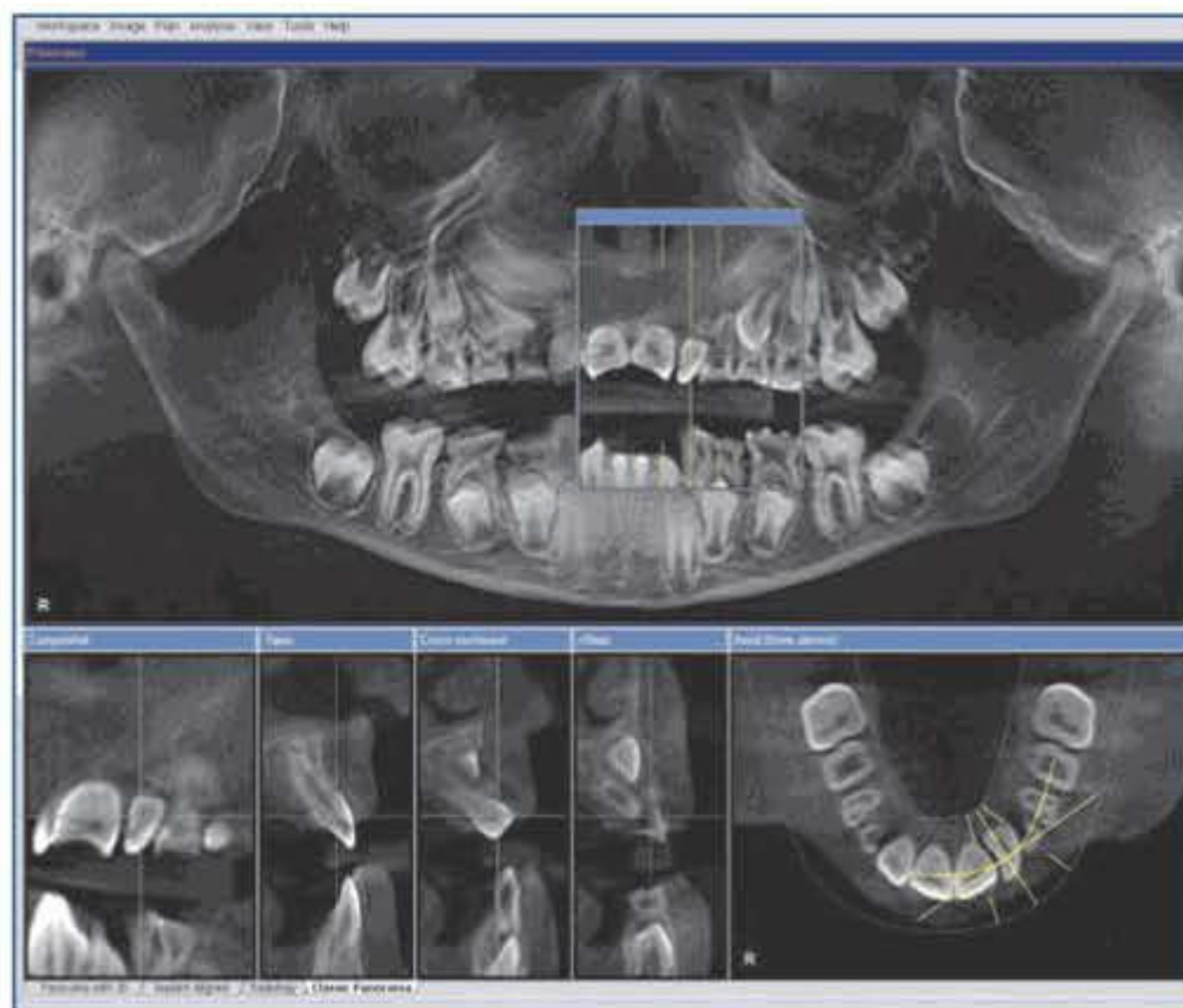


Fig 8-3 A 10-year-old boy with initial orthodontic findings. In addition to the ectopic tooth 13, there is a pronounced distal rotation of tooth 22 with palatal tipping of its root arising from the lack of space in the dental arch.

8.2.2 Rotations

Teeth frequently have to be derotated in the context of orthodontic treatment. Rotations that are clinically invisible or not identifiable in 2D imaging (Figure 8-2a) frequently occur in the apical region (Figure 8-2b). Likewise, clinically visible rotations can be traced to the roots (Figure 8-3). Three-dimensional imaging permits a precise definition of rotations so that relapse can be effectively counteracted.



Fig 8-4 A 12-year-old boy with facial asymmetry and consequent palatal tipping in the right posterior region of the maxilla. Lack of space resulted in displacement of tooth 12 in a palatal direction, tooth migrations and a consequent dentoalveolar anterior midline shift to the right.

8.2.3 Dental Midline Discrepancies

In an alveolar midline discrepancy, which can occur both in the maxilla and the mandible, the teeth are tilted to the right or left on their respective base or have migrated across the midline. Clinically, and on a dental cast, the alveolar midline discrepancy is assessed in relation to the skeletal midline (palatine raphe). Since the visible plane of symmetry is absent in the mandible, an x-ray image (panoramic tomograph, mandibular occlusal radiograph) is also necessary for evaluation of any tipping or migration of the anterior teeth.² A midline discrepancy arising from the migration of the incisors is distinguished from a skeletal midline discrepancy or serious skeletal asymmetries. Therefore, additional conventional radiographic views must be evaluated (preferably PA skull radiographs or maxillary/mandibular occlusal radiographs). Modern 3D imaging procedures can provide detailed information on both asymmetries and structural anomalies.

The anterior midline displacement of the permanent teeth in the maxilla and mandible is an important diagnostic criterion for evaluating midline discrepancies and determining the related therapy. To supplement initial orthodontic records, the deviation of the anterior midline of the maxilla from the spina plane (Figure 8-4) and the deviation of the anterior midline of the mandible from the mental spine is diagnosed in the 3D imaging. With an alveolar anterior midline discrepancy, the spina plane and the mental spine correspond with the median section of the skull, but the contact point with the upper and lower incisors is displaced.

8.2.4 Transposition

The term transposition is used when there is a major displacement of the tooth buds and the positions of teeth are switched. This is most frequently observed in the upper dental arch in the posterior region between the permanent canines and the upper first premolars (Figure 8-5).⁴ Transpositions arise from an ectopic position of the tooth buds and are especially promoted by the long eruption path of the upper permanent canines (Figure 8-6).

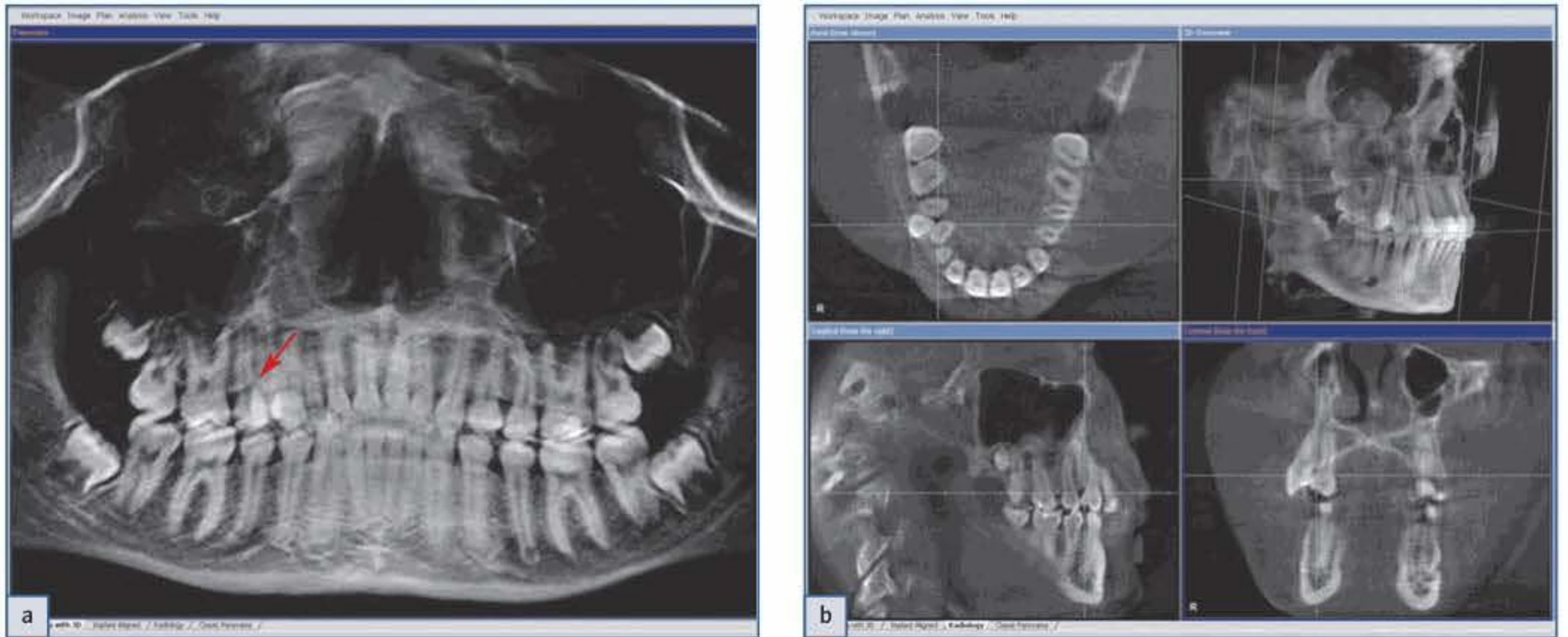


Fig 8-5 A 13-year-old girl with initial orthodontic findings. (a) In the panoramic view, a questionable displacement (arrow) in the right maxillary anterior region can be discerned. (b) The buccal location of tooth 13 between 14 and 15 can be evaluated in the axial and coronal view of the 3D image. The mesial migration of tooth 14 caused the transposition of 14 and 13. In view of the lack of space, the extraction of 14 and alignment of 13 in the dental arch was planned.

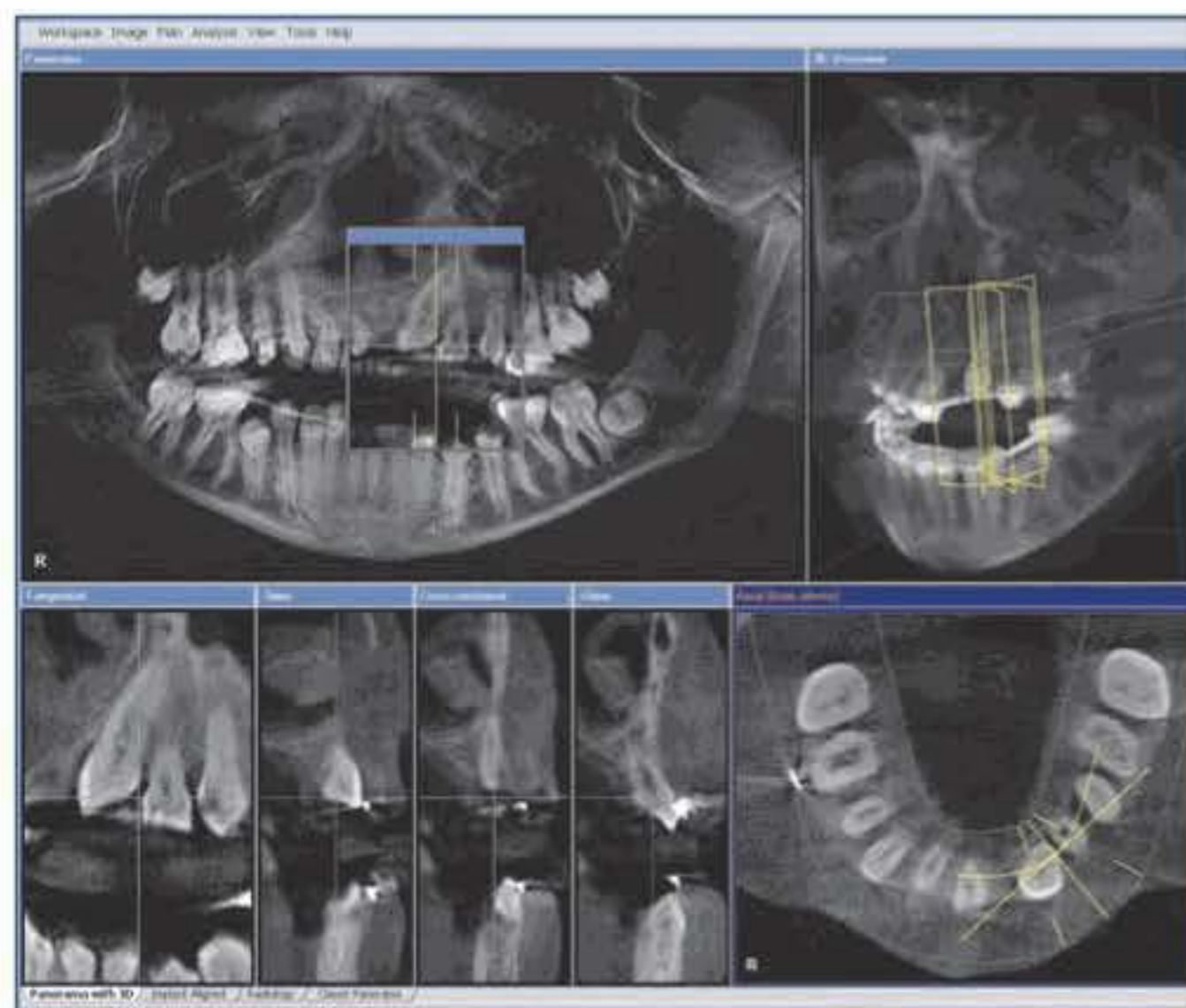


Fig 8-6 A 14-year-old female with dilacerations of teeth 11 and 12 of uncertain origin. Transposition of 22 and 23, and extraction of 15, 25 and 21 occurred in ongoing orthodontic therapy. The advanced root development of teeth 23 and 22 prevented the orthodontic movement into the normal arch position.

8.2.5 Eruption Disturbances

Under normal conditions, a tooth erupts through the oral mucosa when the root has developed to two-thirds of its length. Unerupted teeth are frequently found to have a root that has developed further. The eruption of the tooth can be hindered by various mechanisms, including disturbances in root resorption of the deciduous tooth (Figure 8-7). Undermining resorption in the anterior region or primary crowding in mixed dentition with resorption of the upper deciduous cuspids by

the neighboring permanent lateral incisors restrict the buccal segments from a mesial direction. Lack of space, unusual eruption paths, excess teeth or a thickening of the mucosa after extraction lead to eruption disturbances of permanent teeth (Figures 8-8 and 8-9).³

Another frequent reason for the inhibition of tooth eruption is undermining resorption in the posterior region.⁵ This undermining resorption of the deciduous second molars by the permanent first molars in the maxilla is an expression of the inadequate development of the molar fields and the mesial direction of eruption of the permanent first molars. The first molars are partially impacted through this eruption disturbance. The eruption of the first molars with the premature loss of the deciduous second molars causes the buccal segments to be strongly restricted in a distal direction (Figure 8-10).⁵



Fig 8-7 A 12-year-old girl in ongoing orthodontic treatment. The absence of resorption of the mesial roots of teeth 75 and 85 with the distal eruption of teeth 35 and 45 can be clearly seen in the transverse slices of the panoramic view.



Fig 8-8 A 14-year-old male in ongoing orthodontic treatment. The asymmetrical eruption of the mandibular second premolars seen in the panoramic radiograph (a) arises from root development deviation, the thickened mucosa at 45, as well as the restricted space owing to the distal rotation of the tooth, which is visible in the axial radiograph (b).

Fig 8-9 An 11-year-old boy after surgery for cleft lip and palate and extraction of macrodontic teeth 12 and 22, with marked crowding in all buccal segments. As compensation, teeth 35 and 45, which were impacted in a lingual direction, were extracted.

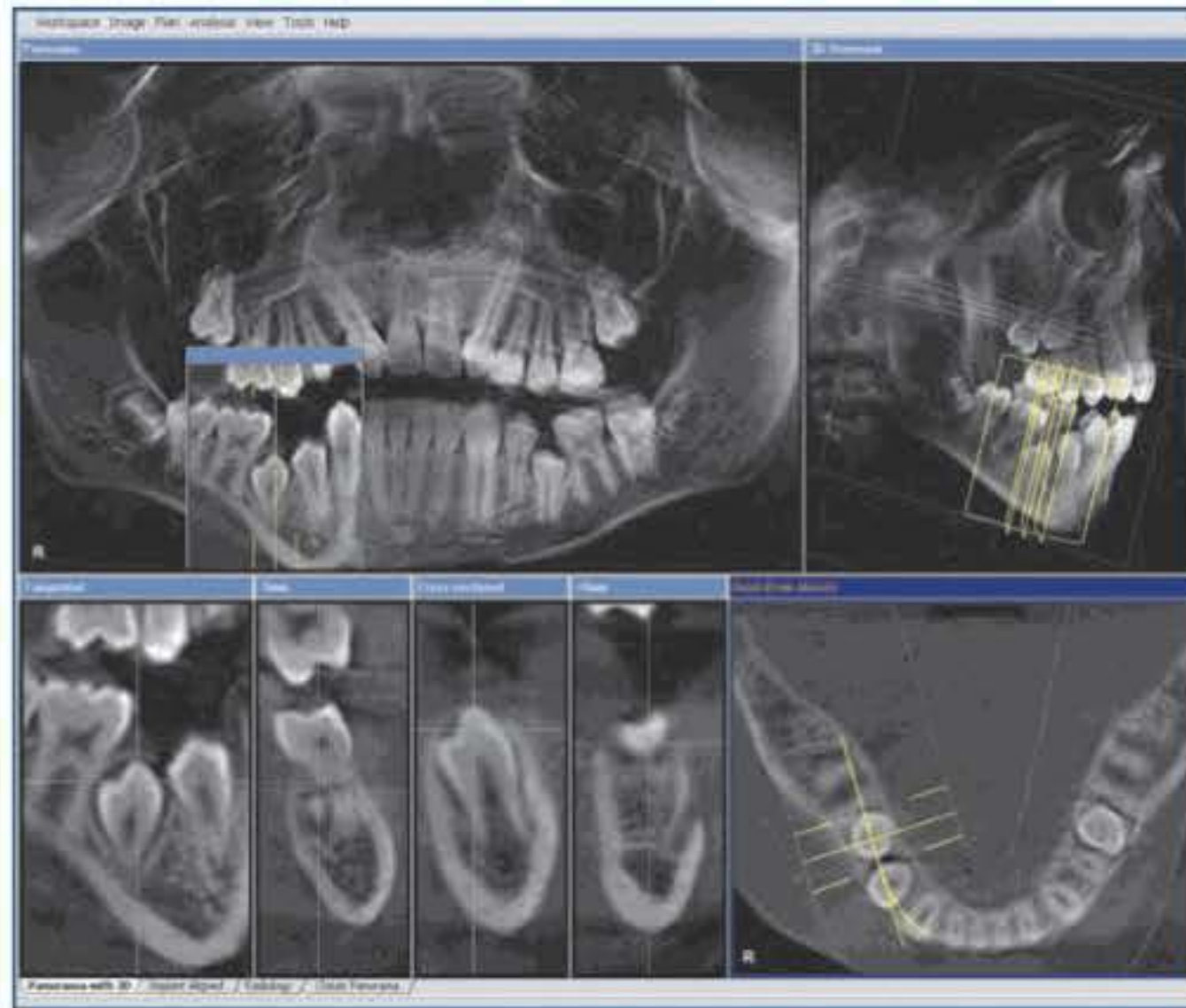
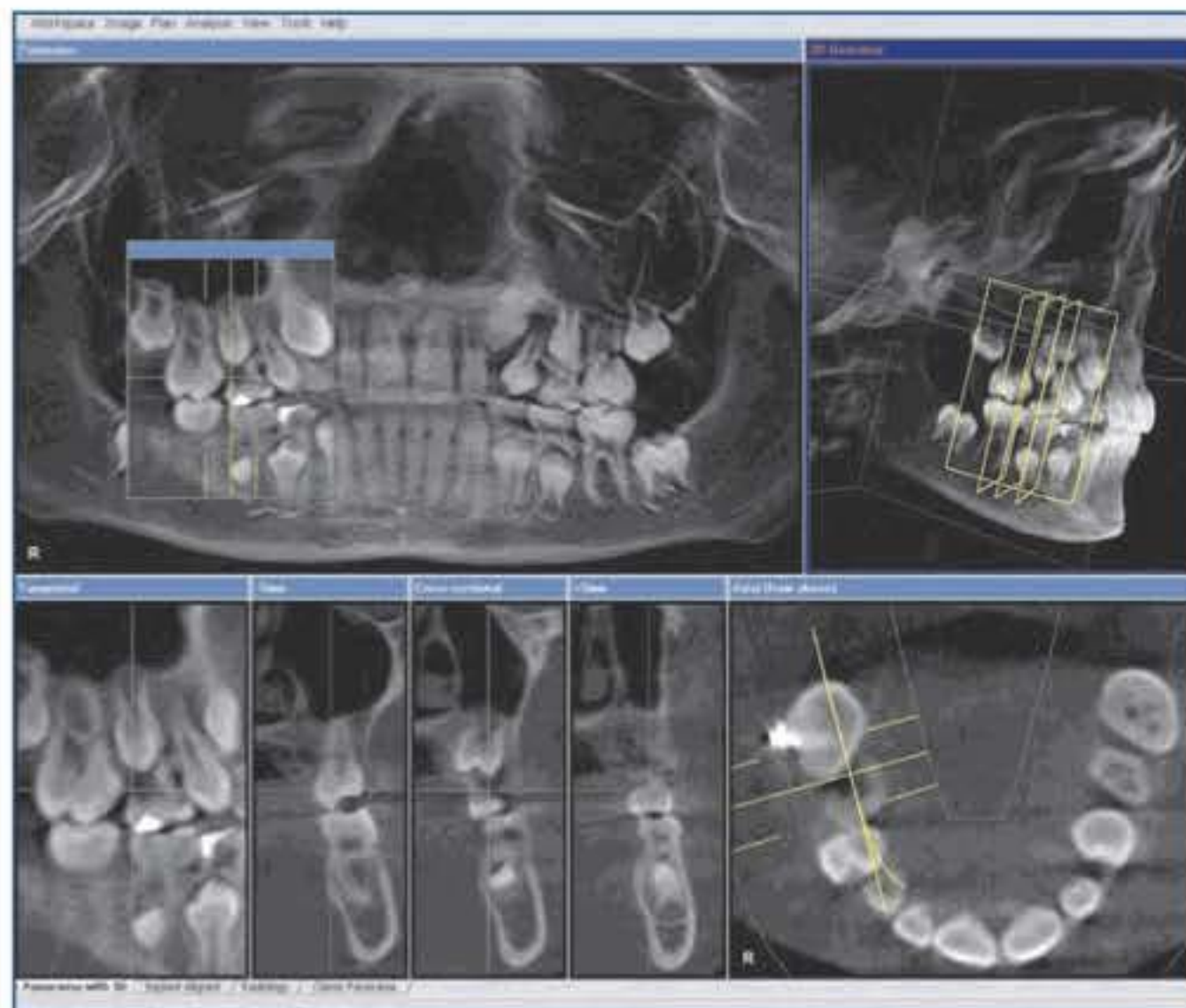


Fig 8-10 A 10-year-old girl with initial radiological findings. The clinically invisible mesial migration of tooth 16 identifiable in the axial radiographic view arises from the undermining resorption of tooth 55 by the erupted tooth 16, with prospective crowding in the right maxillary buccal segment.



8.3 Malpositions of Groups of Teeth

8.3.1 Narrow Germ Position

Crowding can occur in both the anterior and posterior segments and is one of the most frequent tooth position anomalies. The reasons for crowding are many and can arise from the sagittal or transverse underdevelopment of the jaw (Figure 8-11), a discrepancy between tooth size and jaw size (so-called primary crowding), a restriction of the posterior segments (secondary crowding) or mesial drift of the posterior teeth (tertiary crowding).^{5,6} A lack of space expresses itself by the

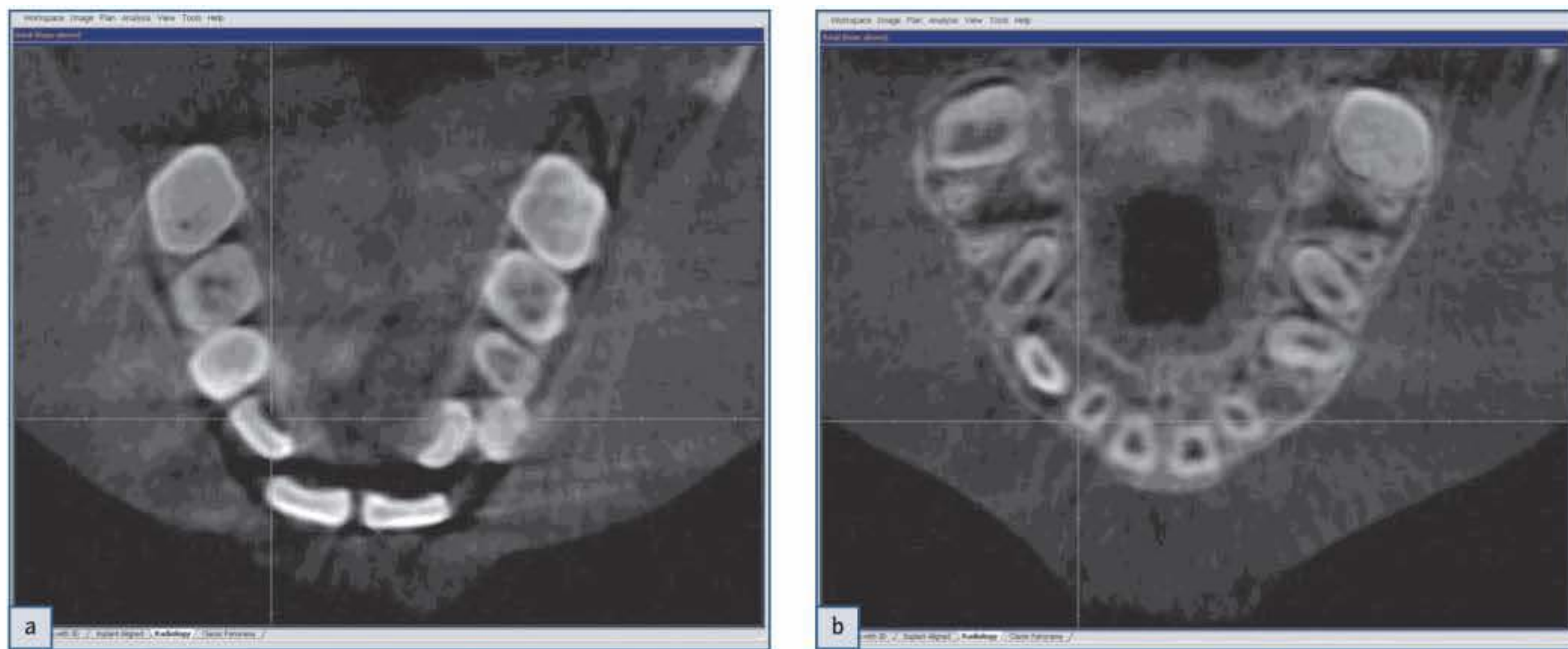


Fig 8-11 A 9-year-old boy with pronounced crowding in the maxilla and transverse discrepancy of width between the maxilla and mandible. (a) In the incisal axial radiograph, the palatal displacement of teeth 12 and 22 is visible, as well as the direct proximity of teeth 12 and 14. (b) Proceeding further in an apical direction, the tooth bud of 13 is directly adjacent to the tooth bud of 15, whereas in the second quadrant the roots of 24 and 25 are cut in the axial view.



Fig 8-12 A 7-year-old girl with previously operated cleft lip and palate. (a) Pronounced crowding of the mixed dentition can be seen in both the maxilla and mandible. (b) The crowding can be seen in the axial radiograph to have caused buccal displacement of teeth 33 and 43, leading to distal rotation of teeth 32 and 42. The ectopic crown of 33 with palatal displacement of the root of 32 is identifiable in the transverse radiograph.

staggering of the incisors (Figure 8-12a) or a buccal or palatal displacement of the posterior teeth (Figures 8-12b and 8-13), and can lead to a narrow germ position in the posterior segments or retention of a permanent tooth in the jaw.

With the aid of the 3D image, the localization of the teeth in the dental arch can be precisely evaluated, since the image has no overlapping and is true to detail.



Fig 8-13 A 12-year-old girl undergoing orthodontic treatment. The palatal displacement of tooth 15 with marked crowding in the maxilla is clearly visible.

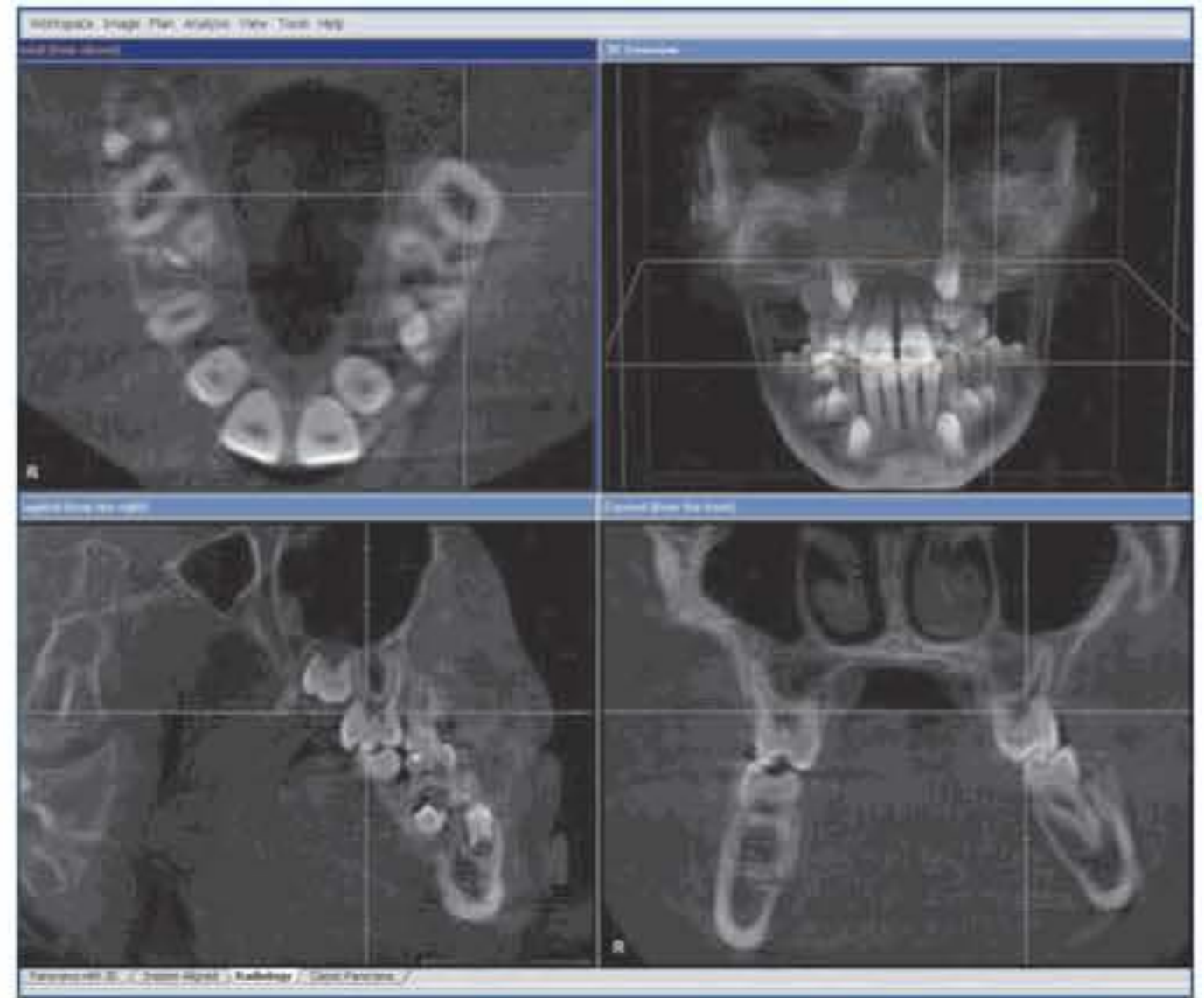


Fig 8-14 A 9-year-old boy with pronounced crowding in the maxilla and transverse discrepancy between the maxilla and mandible. The basal discrepancy is clearly visualized in the anterior and coronal view. In addition to assessing the origin of the width discrepancy, the 3D radiograph allows an estimate of the root growth of the teeth in the posterior region of the maxilla if they are to be used to anchor a maxillary expansion appliance.

8.3.2 Posterior Cross-bite

In eugathic dentition, the teeth in the maxilla overlap the teeth of the mandible in both the anterior and posterior regions, and the palatal cusps engage in the central fissures of the lower premolars and molars. In a posterior cross-bite, this reliable transverse occlusion does not exist and the buccal cusps of the posterior mandibular teeth overlap those of the posterior maxillary teeth. Individual teeth or the entire group of teeth can be affected.

Three-dimensional imaging enables the orthodontist to determine the cause for the transverse discrepancy with the aid of the coronal slices. Its origin can lie in a transverse discrepancy in the apical base or a buccal or lingual tipping of individual teeth (Figure 8-14).

8.4 Skeletal Deviations

8.4.1 Lateral Cephalographs

The lateral cephalograph (a "ceph view"), introduced to dentistry in 1931 by *Broadbent*, is an essential tool for diagnosing and planning therapy in orthodontics and oro-maxillofacial surgery. This x-ray image of the skull in the *norma lateralis* (the side view) provides the dentist with valuable information on the vertical and sagittal structure of the facial skull that cannot be obtained by any other diagnostic measure. By agreement, the right side of the patient is viewed.

A major advantage of this imaging view is that all of the bony structures of the neurocranium and visceral cranium can be visualized, as can the covering facial soft tissue when a corresponding filter is used. Depending on the source-to-film distance, a nearly dimensionally true and sharp image of the skull is attained that simplifies the metric analysis of the anatomical structures.¹ The overarching term for the numerous analyses is radiographic cephalometry (Greek: *kephalé*: head; *metrión*: measure).

The lateral cephalograph enables orthodontists to draw conclusions about the size and shape of the jaws, their position in sagittal and vertical relation to the anterior base of the skull, and their position in relation to each other. In addition, information is obtained on the axial inclination of the anterior and posterior teeth in a sagittal direction, the extent of the surrounding alveolar bone, and the relationship of the anterior teeth to the facial soft tissue.⁷ Furthermore, the sagittal and vertical position of displaced teeth and the openness of the nasopharynx can be evaluated. The information from the lateral cephalograph generally plays a major role in the planning of orthodontic treatment since it not only reveals the anatomical structural causes of the clinical picture but also enables an estimation of therapeutic feasibility.⁶ Since the lateral cephalograph only captures a momentary image, an individual film cannot be used to predict growth in young patients. Overlapping images that have been taken over a long period can provide a certain amount of information about the extent and direction of growth processes and provide clues about morphological changes that can be expected over the remaining growth period. However, the primary problem with overlapping lateral cephalographs is that it is nearly impossible to place the patient in an identical position each time, which greatly impairs the precision of such comparisons. In general, all photometric analyses of conventional lateral cephalographs suffer from a certain degree of measuring imprecision because of the imaging technique (magnification factor as a function of the source-to-film distance) and direction of projection (position of the patient in the cephalostat).¹ Any interpretation of cephalometric values must take these deviations into consideration. The measuring results should never be used uncritically in setting therapeutic goals.

Lateral cephalographs are also very important for diagnosis and planning therapy in oro-maxillofacial surgery. In addition to the above-mentioned information provided by these images, oro-maxillofacial surgeons can use lateral cephalographs to help to plan surgery and to simulate the effects of surgery on the patient's external appearance. A supportive role is played by computer programs that measure the planned changes in the bony structures and calculate the envisioned influence on the soft tissue profile. This procedure, known as the *visualized treatment objective*, can help to determine the more advantageous operation for the patient in unclear situations. Again, certain deviations between the computer simulation and actual postoperative appearance of the patient must be taken into account.

Three-dimensional imaging of craniofacial structures promises much greater precision and reliability of the simulation in this area as well as in other indications.

The 3D visualization software can generate a 2D lateral image from the 3D data set (Figures 8-15a, 8-16a and 8-17a). It is 150 mm thick and extends through the entire 3D volume. It is aligned to sagittal, coronal and axial reference planes. The generated lateral x-ray image can be imported at a resolution of 96 dpi into evaluation programs for lateral cephalographs and traced and evaluated to assist with the orthodontic diagnosis (Figures 8-15b,c, 8-16b,c and 8-17b,c).

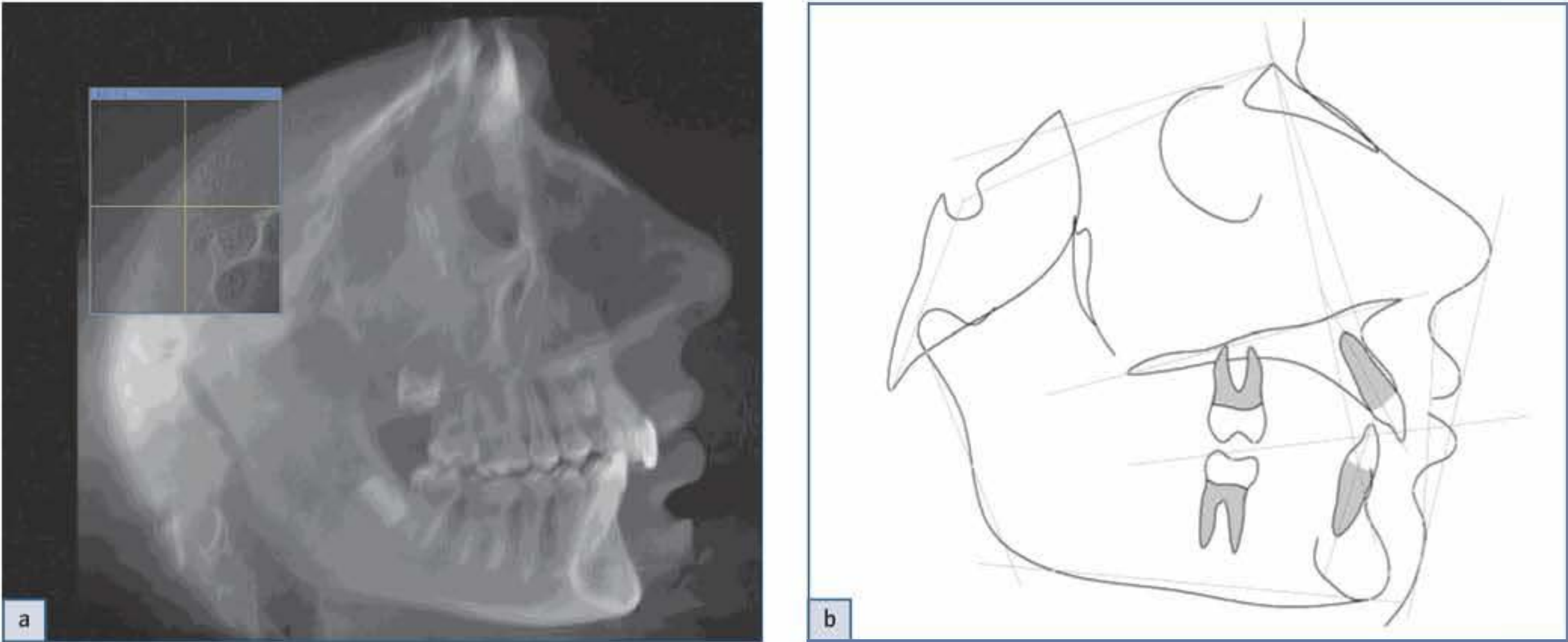
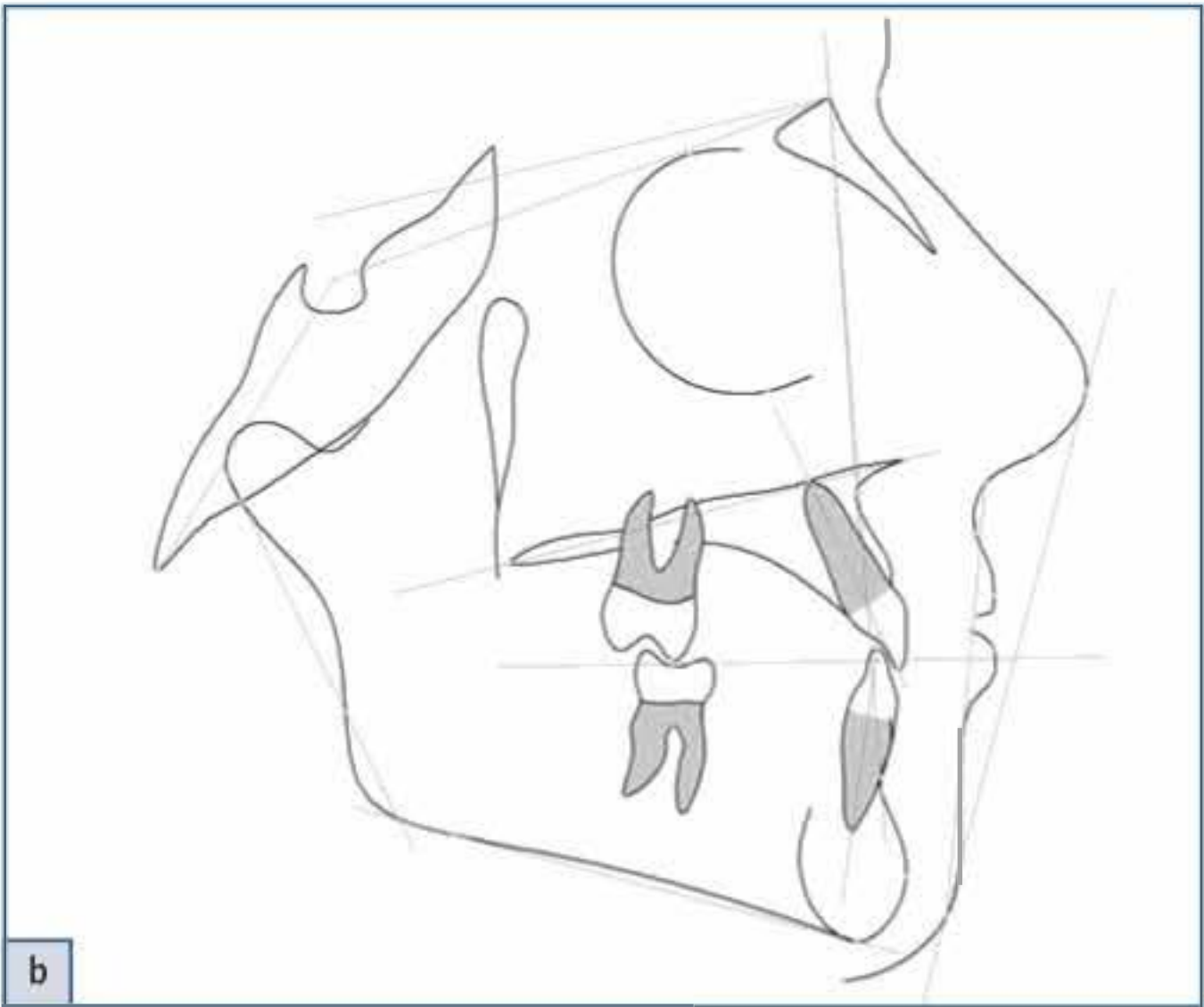
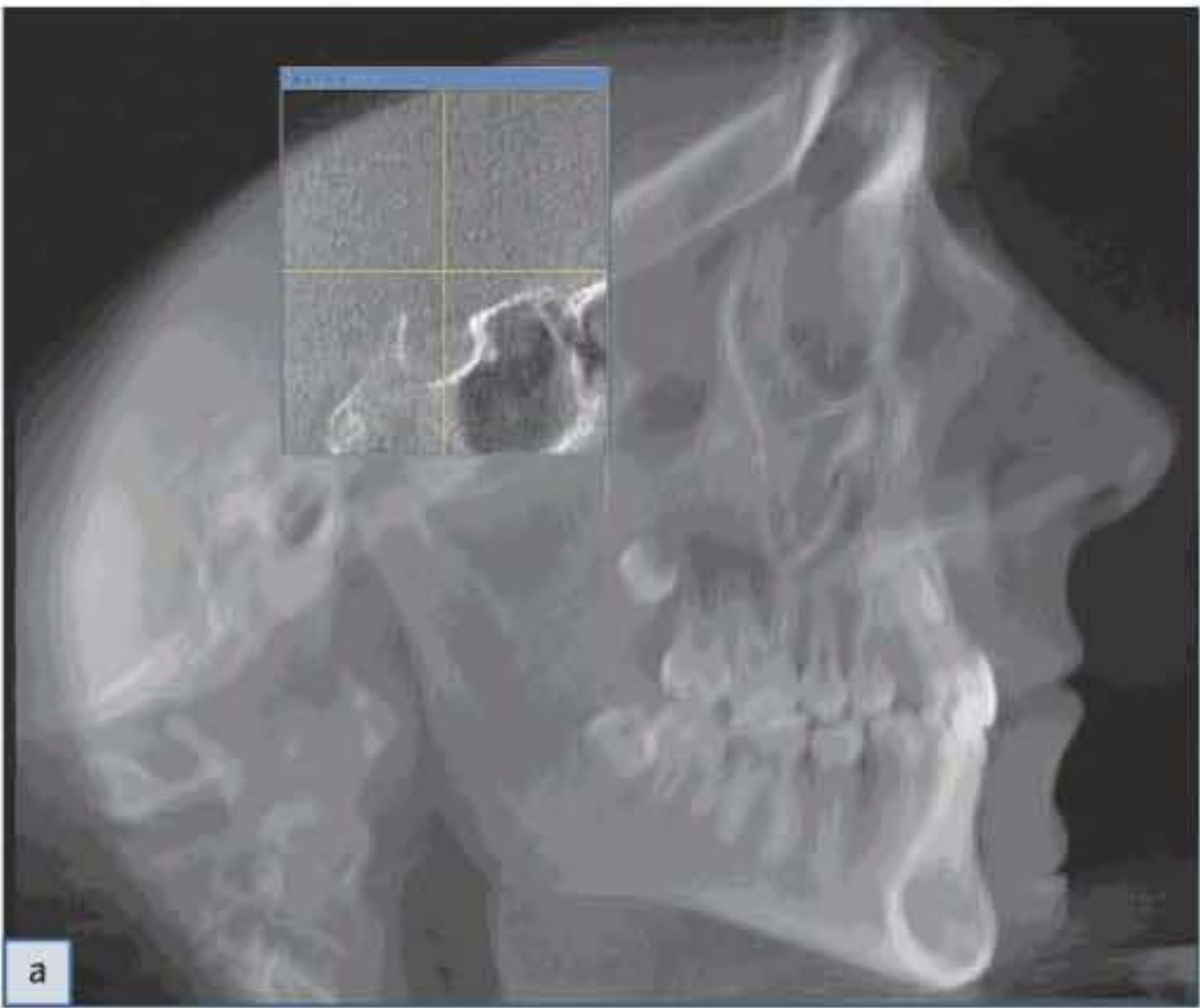


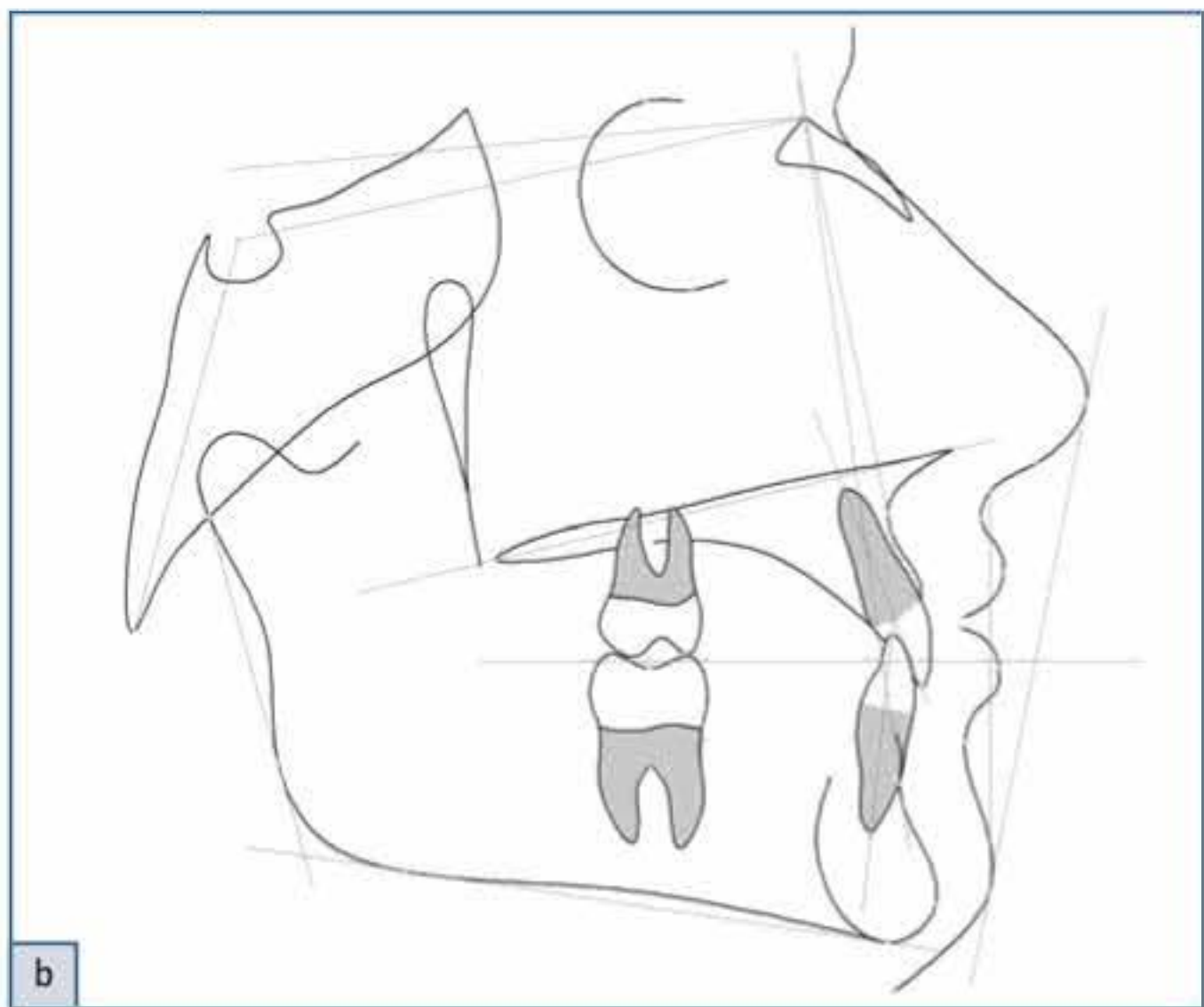
Fig 8-15 A 13-year-old girl with a clinically enlarged vertical overbite and distal occlusion. A correlative harmony evaluation (b) revealed an orthognathic facial type with a disto-basal jaw relation, horizontal skull configuration with reduced mandibular basal angle and contour angle with a tendency toward a convex profile structure. SNA, angle between sella-nasion line and nasion-subspinale line; NL-NSL, nasel line to nasion-sella line; ML-NL, mandibular line-nasal line; WSBa, angle between the nasion-sella line and sella-basion line. (The evaluation of the images with the diagnostic software fr-win was performed with the kind assistance of computerkonkret.)

	SNA angle	NL-NSL	NSBa angle	ML-NSL	SNB angle	MI-NL
retrognathic	62.0	14.0	141.0	43.0	64.0	28.0
	63.0	13.5	140.0	42.0	65.0	28.0
	64.0	13.0	139.0	41.0	66.0	27.0
	65.0	12.5	138.0	40.0	67.0	26.0
	66.0	12.0	137.0	39.0	68.0	25.0
	67.0	11.5	136.0	38.0	69.0	25.0
	68.0	11.0	135.0	37.0	70.0	24.0
	69.0	10.5	134.0	36.0	71.0	23.0
	70.0	10.0	133.0	35.0	72.0	22.0
	71.0	9.5	132.0	34.0	73.0	21.0
orthognathic	72.0	9.0	131.0	33.0	74.0	20.0
	73.0	8.5	130.0	32.0	75.0	19.0
	74.0	8.0	129.0	31.0	76.0	18.0
	75.0	7.5	128.0	30.0	77.0	17.0
	76.0	7.0	127.0	29.0	78.0	16.0
	77.0	6.5	126.0	28.0	79.0	15.0
	78.0	6.0	125.0	27.0	80.0	14.0
	79.0	5.5	124.0	26.0	81.0	13.0
	80.0	5.0	123.0	25.0	82.0	12.0
	81.0	4.5	122.0	24.0	83.0	11.0
prognathic	82.0	4.0	121.0	23.0	84.0	10.0
	83.0	3.5	120.0	22.0	85.0	9.0
	84.0	3.0	119.0	21.0	86.0	8.0
	85.0	2.5	118.0	20.0	87.0	7.0
	86.0	2.0	117.0	19.0	88.0	6.0
	87.0	1.5	116.0	18.0	89.0	5.0
	88.0	1.0	115.0	17.0	90.0	4.0
	89.0	0.5	114.0	16.0	91.0	3.0
	90.0	0.0	113.0	15.0	92.0	2.0
	91.0	0.0	112.0	14.0	93.0	1.0



	SNA angle	NL-NSL	NSBa angle	ML-NSL	SNB angle	ML-NL
retrognathic	82.0	14.0	141.0	43.0	64.0	28.0
	83.0	13.5	140.0	42.0	65.0	
	84.0	13.0	139.0	41.0	66.0	27.0
	85.0	12.5	138.0	40.0	67.0	
	86.0	12.0	137.0	39.0	68.0	26.0
	87.0	11.5	136.0	38.0	69.0	
	88.0	11.0	135.0	37.0	70.0	25.0
	89.0	10.5	134.0	36.0	71.0	
	90.0	10.0	133.0	35.0	72.0	24.0
	91.0	9.5	132.0	34.0	73.0	
orthognathic	92.0	9.0	131.0	33.0	74.0	23.0
	93.0	8.5	130.0	32.0	75.0	
	94.0	8.0	129.0	31.0	76.0	22.0
	95.0	7.5	128.0	30.0	77.0	
	96.0	7.0	127.0	29.0	78.0	21.0
	97.0	6.5	126.0	28.0	79.0	
	98.0	6.0	125.0	27.0	80.0	20.0
	99.0	5.5	124.0	26.0	81.0	
	100.0	5.0	123.0	25.0	82.0	19.0
	101.0	4.5	122.0	24.0	83.0	
prognathic	102.0	4.0	121.0	23.0	84.0	18.0
	103.0	3.5	120.0	22.0	85.0	
	104.0	3.0	119.0	21.0	86.0	17.0
	105.0	2.5	118.0	20.0	87.0	
	106.0	2.0	117.0	19.0	88.0	16.0
	107.0	1.5	116.0	18.0	89.0	
	108.0	1.0	115.0	17.0	90.0	15.0
	109.0	0.5	114.0	16.0	91.0	
	110.0	0.0	113.0	15.0	92.0	14.0
	111.0			14.0	93.0	
	112.0			13.0	94.0	13.0
	113.0				95.0	
	114.0				96.0	12.0
	115.0				97.0	
	116.0				98.0	

Fig 8-16 A 13-year-old girl with neutral occlusion and normal sagittal and vertical overbite, plus slightly convex facial profile. (b) The correlative harmony evaluation revealed a skeletal class II with a distobasal jaw relation owing to mandibular and maxillary retrognathia, a reduced contour angle tending towards a convex profile structure, a vertical skull configuration with an enlarged mandibular basal angle and retrusion of the maxillary anterior teeth. Abbreviations as in Fig 8-15. (The evaluation of the images with the diagnostic software fr-win was performed with the kind assistance of computerkonkret.)



	SNA angle	NL-NSL	NSBa angle	ML-NSL	SNB angle	ML-NL
retrognathic	62.0	14.0	141.0	43.0	64.0	28.0
	63.0	13.5	140.0	42.0	65.0	28.0
	64.0	13.0	139.0	41.0	66.0	27.0
	65.0	12.5	138.0	40.0	67.0	27.0
	66.0	12.0	137.0	39.0	68.0	26.0
	67.0	11.5	136.0	38.0	69.0	25.0
	68.0	11.0	135.0	37.0	70.0	25.0
	69.0	10.5	134.0	36.0	71.0	24.0
	70.0	10.0	133.0	35.0	72.0	24.0
	71.0	9.5	132.0	34.0	73.0	23.0
orthognathic	72.0	9.0	131.0	33.0	74.0	23.0
	73.0	8.5	130.0	32.0	75.0	22.0
	74.0	8.0	129.0	31.0	76.0	21.0
	75.0	7.5	128.0	30.0	77.0	21.0
	76.0	7.0	127.0	29.0	78.0	20.0
	77.0	6.5	126.0	28.0	79.0	20.0
	78.0	6.0	125.0	27.0	80.0	19.0
	79.0	5.5	124.0	26.0	81.0	19.0
	80.0	5.0	123.0	25.0	82.0	18.0
	81.0	4.5	122.0	24.0	83.0	18.0
prognathic	82.0	4.0	121.0	23.0	84.0	17.0
	83.0	3.5	120.0	22.0	85.0	17.0
	84.0	3.0	119.0	21.0	86.0	16.0
	85.0	2.5	118.0	20.0	87.0	16.0
	86.0	2.0	117.0	19.0	88.0	15.0
	87.0	1.5	116.0	18.0	89.0	15.0
	88.0	1.0	115.0	17.0	90.0	14.0
	89.0	0.5	114.0	16.0	91.0	14.0
	90.0	0.0	113.0	15.0	92.0	13.0
	91.0	0.0	112.0	14.0	93.0	13.0

Fig 8-17 A 12-year-old boy with prognathism without any family associating history. (b) The correlative harmony evaluation revealed a skeletal class III with a mesiobasal jaw relation and mandibular and maxillary prognathism, a horizontal skull configuration with a reduced mandibular basal angle, anterior inclination of the maxilla and retrusion of the anterior maxillary and mandibular teeth. Abbreviations as in Fig 8-15. (The evaluation of the images with the diagnostic software fr-win was performed with the kind assistance of computerkonkret.)



Fig 8-18 A 12-year-old boy with congenital facial asymmetry of an unclear etiology. The pronounced facial asymmetry arises from a hypoplasia of the right ramus and body of the mandible, resulting in a right concave profile with a shift of the chin to the right. The pronounced dental compensation of the occlusion is manifested in the 3D radiograph by a buccal tilt in the right maxillary posterior teeth and a lingual tilt in the left mandibular posterior teeth.

8.4.2 Asymmetries

When considering facial symmetries in a differential diagnosis, a distinction must be drawn between function-related lateral deviations of the mandible (lateral forced bites) and skeletal, unilateral maldevelopments of the facial skeleton.² In addition, facial symmetry can be influenced by the differences between the sides in thickness or condition of the facial soft tissue.

Facial asymmetries can involve different areas of the skull or the mandible. Mandibular asymmetry is expressed as a one-sided deviation of the center of the mandible from the median sagittal plane (Figure 8-18). Craniofacial asymmetries frequently also exhibit deviations of transverse planes within the vertical plane. In clinical diagnostics, the midline discrepancy is expressed as a deviation of the midlines of the maxillary and mandibular teeth.

The 3D radiograph reveals maldevelopments and deviations in the shape, size and position of the skeletal structures.

8.5 Summary

Malocclusions can involve deviations in tooth position as well as sagittal, vertical and transverse deviations in the positional relationship between maxilla and mandible. Each malocclusion can be traced to functional, dentoalveolar or skeletal causes. The individual findings obtained in orthodontic diagnostics permit the establishment of a differential diagnosis and the combination of the individual findings into an overall orthodontic summary, which can then be addressed in orthodontic therapy.

Radiographic 3D diagnostics provides the orthodontist with information that greatly influences the treatment plan. Dentoalveolar malpositions in the mesodistal or buccolingual direction can be precisely evaluated and taken into account in therapeutic planning. Occlusal radiographs or dental films of individual teeth can be omitted, since their orthodontic diagnostic value is limited by image distortion. Furthermore, the causes of malpositions of groups of teeth can be identified with 3D diagnostics. When examining skeletal deviations, 3D visualization offers new possibilities for evaluating craniofacial structures, and it promises to permit a more precise differential diagnosis in the future.

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9 Traumatology

Robert A. Mischkowski and Philipp Scherer

9.1 Dentoalveolar Injuries

Dentoalveolar injuries include tooth fractures and luxations as well as alveolar process fractures. Injuries to these structures are among the most frequent in the oro-maxillofacial region. The highly exposed maxillary anterior teeth are especially affected, making up approximately 70% of such injuries.^{1,2}

The basis for diagnosing injuries to teeth and the periodontium is a precise history with a description of the accident, a clinical diagnosis plus imaging. Each tooth within the range of the traumatic force should undergo a sensitivity and mobility test. In deciduous and mixed dentition, loosened teeth and questionable tooth positions can be the result of physiological tooth replacement, which is why patients and their parents must be carefully questioned. The clinical examination is rounded out with checks for occlusal disturbances, occlusal steps as well as hemorrhaging and fissures in the gingiva.

In addition to the clinical diagnosis, a 3D radiological diagnosis is also necessary. An OPG is appropriate as it can provide a large amount of information. One image permits the evaluation of the teeth, alveoles, alveolar process, the entire mandible and large portions of the maxilla.³ Since trauma to the maxillofacial region frequently represents combined injuries to different structures, major injuries can remain hidden from view even in an OPG. Therefore, additional images from different angles should always be taken, so that all fractures can be reliably determined. Specific, individual tooth imaging or caudally eccentric PA projections of the skull according to Clementschitsch are appropriate.⁴ The use of CBVI combines the three dimensions necessary for diagnostics with the information-rich OPG, displacing classic dental radiological techniques when it is available.

9.1.1 Tooth Fractures

Tooth fractures include crown, root and crown–root fractures. Crown fractures are divided into infractions (incomplete fractures), uncomplicated fractures (without the exposure of the pulp) and complicated fractures (with exposure of the pulp). Crown–root fractures are also categorized as uncomplicated (without exposure of the pulp) and complicated (with exposure of the pulp). Root fractures almost always involve exposure of the pulp. A distinction is drawn between transverse and oblique fractures in the coronal, middle and apical third of the root, as well as vertical fractures, which generally are crown–root fractures (Figure 9-1).¹



Fig 9-1 Male patient with an uncomplicated crown fracture of tooth 11 and a transverse root fracture in the middle third of the root that has caused a subluxation of the affected tooth. The seriousness of the trauma has also caused an interforaminal mandibular fracture. The apparent presence of a multiple fracture corresponds to the different fracture lines in the vestibular and lingual compacta, which can be seen in the examination window and in the radiological slices (bottom).

Radiological imaging is particularly useful in diagnosing root fractures. The OPG by itself is insufficient to provide a diagnosis, since fracture lines especially of the anterior teeth frequently cannot be discerned because of the overlap with the spinal column. Dental films are additionally required. When the initial examination is CBVI, multiple imaging become unnecessary.

9.1.2 Luxation, Subluxation and Exarticulation

In a subluxation, the trauma causes damage to the periodontium without the affected tooth leaving the associated alveolus. This causes the tooth to loosen and frequently results in a positional anomaly. With a total luxation, the tooth loses direct contact with its bony alveolus. A distinction is drawn between peripheral luxation (extrusion luxation and lateral luxation), central luxation and exarticulation (total luxation). Central luxations always lead to osseous injuries.¹ A panoramic tomograph is appropriate for radiological diagnostics; it also allows the detection of osseous injuries. Minor changes in the periodontal space can be visualized with supplementary dental films. A CBVI can replace the OPG and dental films.

9.1.3 Alveolar Process Fracture

Partial fractures of the alveolar process arise in nearly all peripheral and central tooth luxations.¹ The much rarer complete fractures of the alveolar process are generally associated with the effects of blunt force on several teeth at once, resulting in the teeth being broken out of the alveolar process together with the surrounding bone.⁵ As numerous concomitant injuries are possible, the diagnostics must always consist of a combination of different images or a single 3D image by CBVI.

9.2 Fracture of the Visceral Cranium

A fracture of the visceral cranium can be suspected if a trauma is accompanied by specific clinical signs. In general, direct signs of a fracture are a deformation of the fractured bone, abnormal mobility of the fragments and crepitation, with a shift of the fragments in relation to each other.

Typical direct signs of a fracture of the visceral cranium include:

- deformation: flattening of the zygomatic process of the zygomatic bone, “dish face”, and telecanthus in central midfacial fractures, lower position of the eye in orbital floor fractures, nasal deviations or saddle nose in nasal bone fractures, occlusal steps or occlusion disturbances in mandibular and central midfacial fractures
- abnormal mobility: of the maxilla or midface in Le Fort fractures, of the nasal root area in nasal skeleton fractures, of the mandible in mandibular fractures, of tooth segments in alveolar process fractures.

Crepitation plays a minor role in diagnosing fractures of the visceral cranium, since it frequently cannot be generated and rarely occurs as a sole symptom.

Hematoma, swelling, pain upon pressure or compression and functional disturbances are general indirect signs of a fracture. Other typical indirect signs of a fracture of the visceral cranium include:

- sensitivity disturbances in the area of the supraorbital nerve (anterior sinus fractures), infraorbital nerve (orbital floor and all midfacial fractures) and the inferior alveolar nerve (maxillary fractures)
- restriction of eyeball motility and double vision in all midfacial fractures with involvement of the orbital floor and in isolated orbital floor fractures
- limited ability to open mouth, chewing and swallowing disturbances in fractures of mandibular, zygomatic bone and zygomatic arch.

The clinical findings must always be supplemented with a conventional x-ray examination in two planes or by 3D radiological imaging. The imaging should be tailored to the clinical findings. CBVI is highly appropriate for this application and is not inferior to CT.

9.2.1 Fracture of the Mandible

Because the mandible is in an exposed location, it is frequently affected by traumatic injury. The literature indicates that 70% of traumatic osseous visceral cranium injuries are mandibular fractures, which are associated with additional fractures of the midface in 15%.⁵ Frequently, fractures are caused by blows to the mandible (e.g. in martial arts and team sports) or by falls in which the chin or ramus of the mandible contact a hard surface.

Mandibular fractures almost exclusively occur at the typical weak points. These include the area of impacted wisdom teeth or canines, which reduce the stability of the jaw with their long roots. Fractures in other locations, such as in the body of the mandible, are rare and occur more frequently as pathological fractures in greatly atrophied jaws. From a topographical perspec-

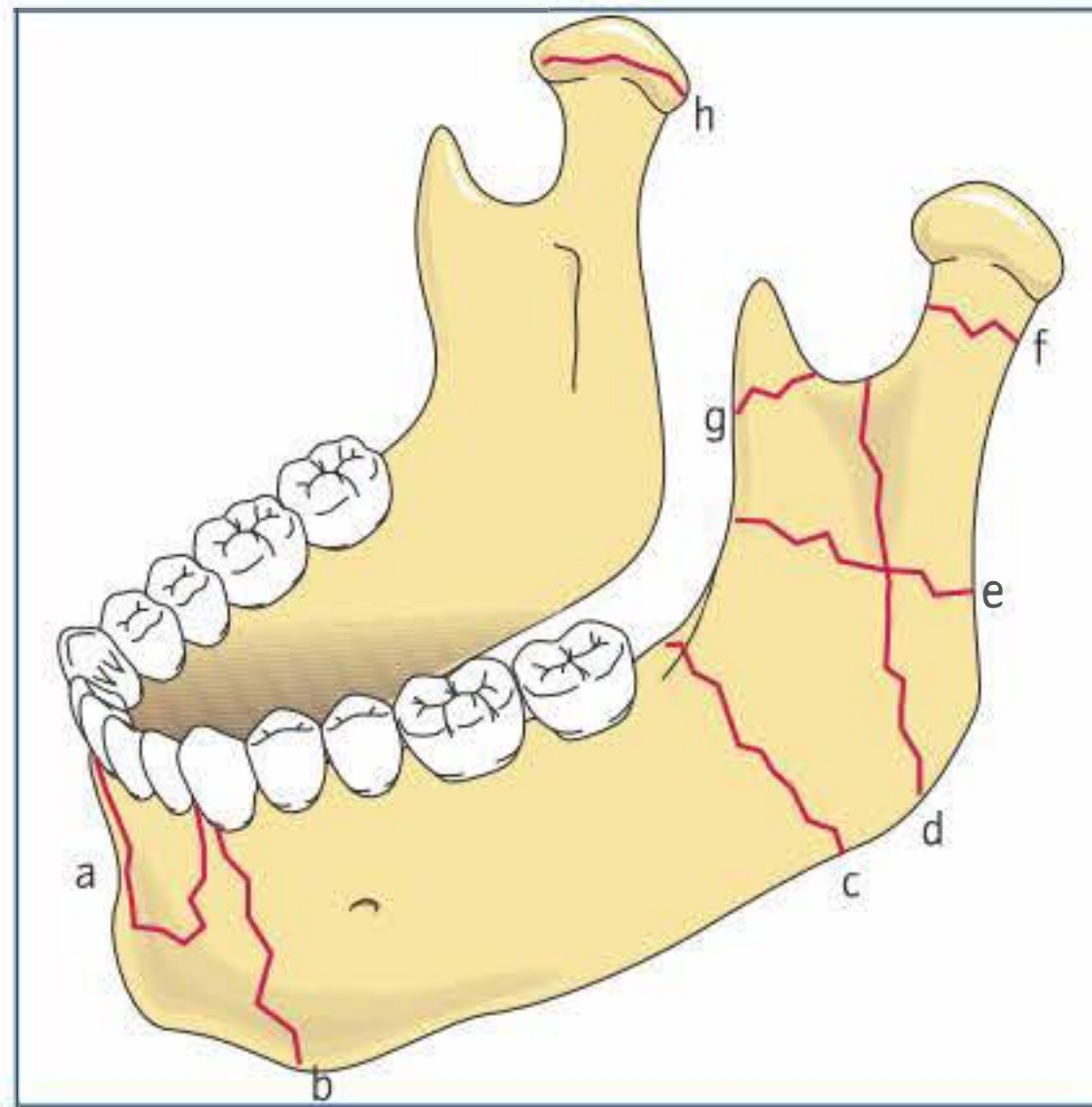


Fig 9-2 *Preferential spots for mandibular fractures:*
 a, alveolar process fracture
 b, interforaminal fracture
 c, mandibular angle fracture
 d, vertical fracture of the ramus of the mandible
 e, horizontal fracture of the ramus of the mandible
 f, condylar fracture
 g, fracture of the coronoid process
 h, capitulum fracture.

tive, which is also pertinent to therapy, mandibular fractures can be divided into five groups (Figure 9-2):⁵

- interforaminal (10–15% of mandibular fractures)
- body of the mandible (5–10%)
- mandibular angle (20–25%)
- ramus of the mandible (2–4%)
- condyloid process (condylus/capitulum) (25–30%)
- coronoid process (approximately 1%).

The mandible frequently experiences double or multiple fractures (Figures 9-3 to 9-6); consequently, if one fracture is identified, other fractures must be sought. Typical combinations of fractures include interforaminal fractures and condylar fractures, paramedian fractures and mandibular angle fractures of the opposing side as well as fractures of both condyloid processes. In addition, fractures of the coronoid process are frequently associated with a depressed fracture of the zygomatic bone on the corresponding side.⁵

Most mandibular fractures can be diagnosed on the basis of their typical clinical symptoms. In addition to the reliable signs of a fracture (deformation, abnormal mobility, crepitation), a series of other typical symptoms are pathognomonic including intraoral and extraoral swelling, hematomas in the area of the fracture site, mucosal tearing, occlusion disturbances, steps in the dental arch, pain upon pressure and compression, loosened teeth, hypesthesia in the area of the inferior alveolar nerve, and functional disturbances such as trismus, mandibular ankylosis and deviations in jaw opening. In addition, condylar fractures can cause bleeding from the outer auditory canal through tearing of the anterior auditory canal wall.

The clinical diagnosis is always followed by a radiological diagnosis. Since the OPG shows the entire mandible, it should be the first radiological examination carried out in mandibular fractures.^{2,3} It also permits screening for potential double or multiple fractures. However, it does have some dis-

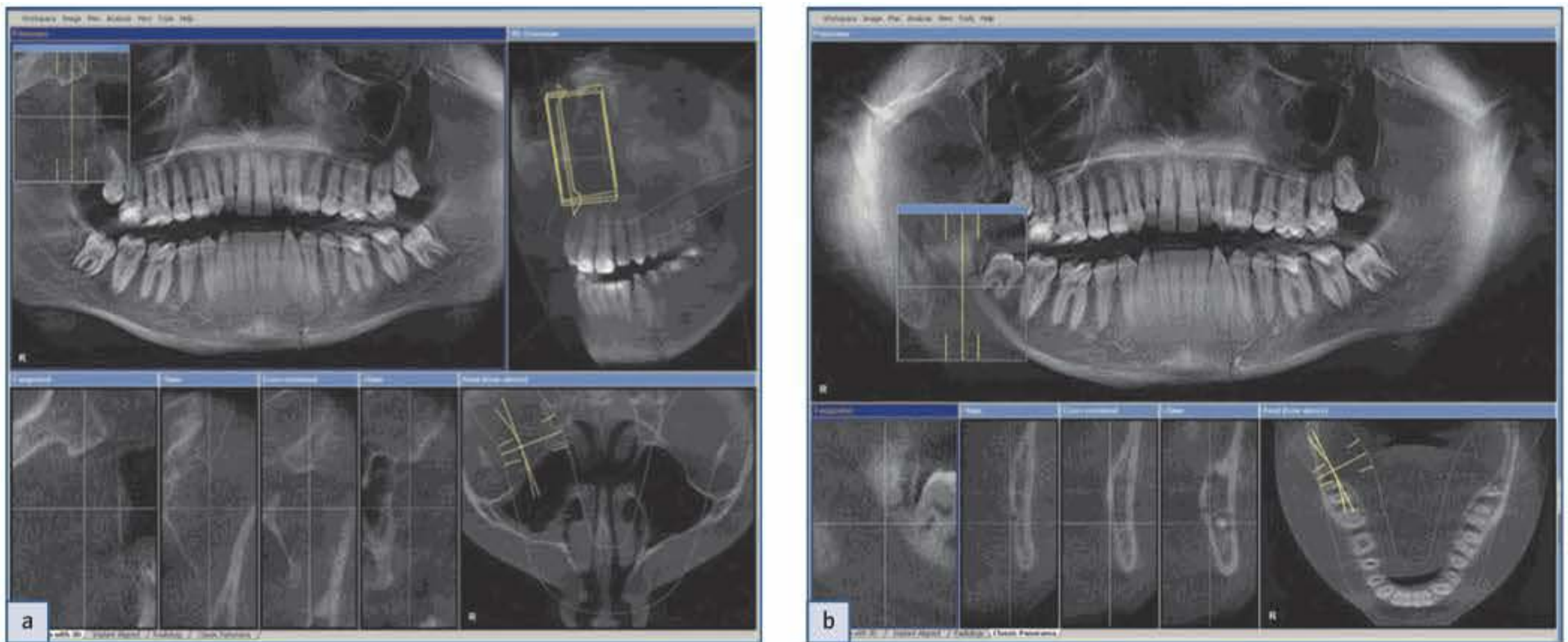


Fig 9-3 Multiple fracture of the mandible with typical combination of fractures (interforaminal, mandibular angle). The fracture lines run along the physiological weak points in the region of the well-formed cuspid root (33) and in the region of the impacted wisdom tooth on the contralateral side (48). The fracture line in the region of the mandibular angle is difficult to visualize in the panoramic view owing to the slight dislocation. However, it can be sufficiently visualized in the examination window (bottom).



Fig 9-4 Fracture of the mandibular ramus; fractures in this region generally occur as pathological fractures in the area of atrophied alveolar processes, as is the case here.

advantages. Since the spinal column overlaps in the anterior region, slightly dislocated interforaminal fractures cannot be reliably visualized. In addition, fractures are frequently displayed with two fracture clefts, which correspond to fracture lines of the inner and outer corticalis. This should not be confused with a segment fracture of the mandible (see Figure 9-1). Dislocated condylus and capitulum fractures cannot be diagnosed solely with the OPC. They can often only be visualized in a PA beam path owing to the medial dislocation that often occurs. When diagnosing the fracture, additional images should always be taken in a second plane. Images in a caudally eccentric PA beam path

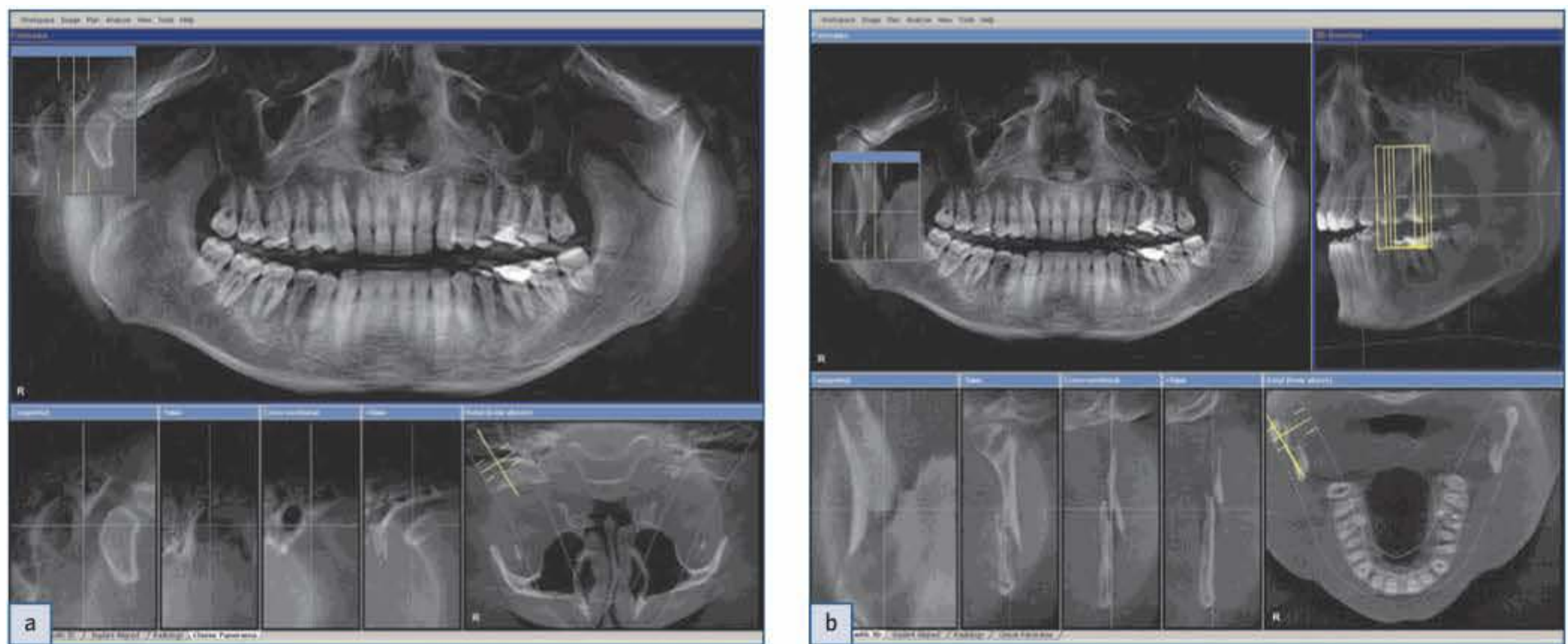


Fig 9-5 Bilateral dislocated condylar fracture. The path of the fracture line in the region of the right mandibular condyle can only be visualized clearly by viewing it in the examination window and in sagittal slices (bottom) owing to the type of dislocation (longitudinal dislocation with contraction).

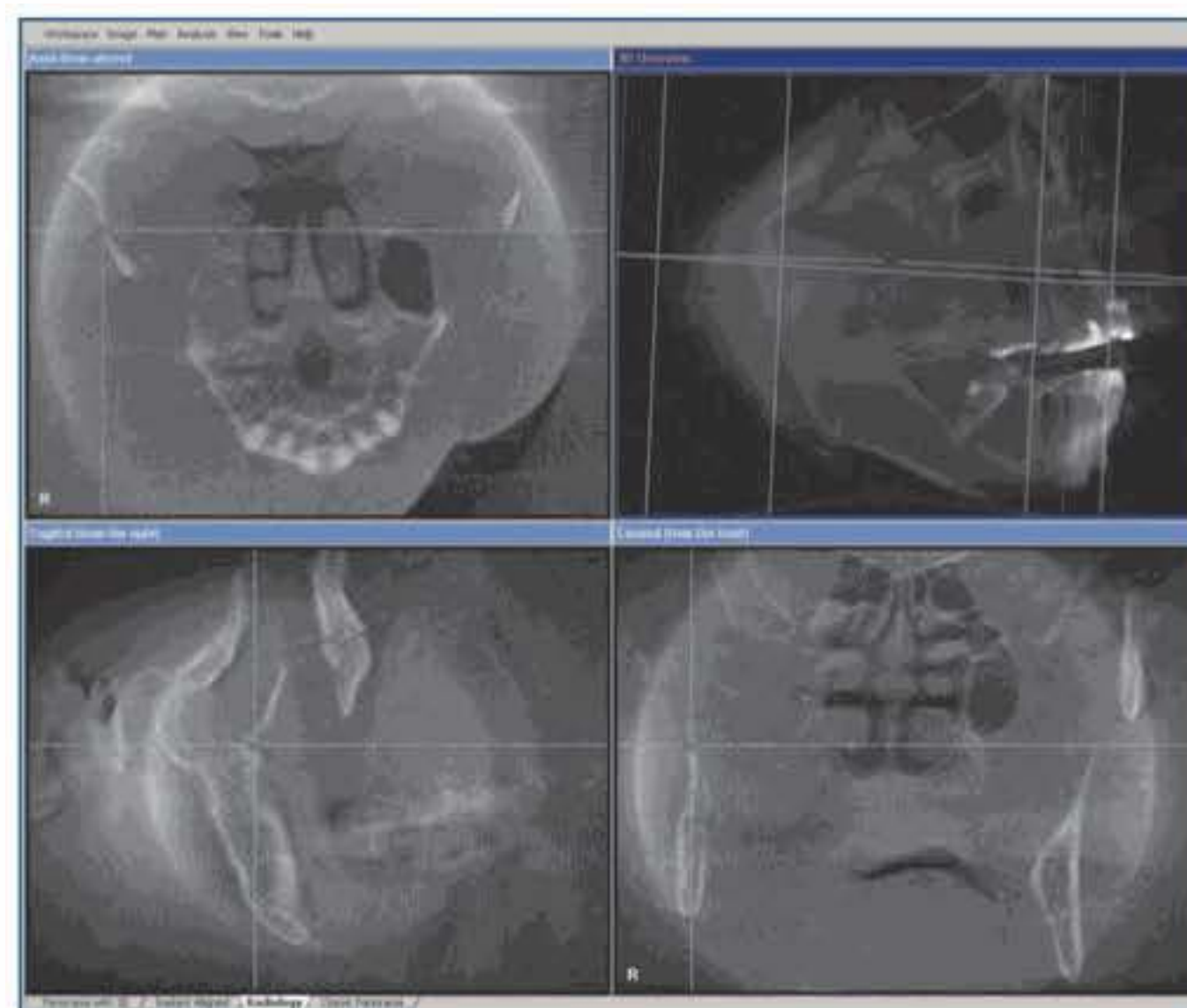


Fig 9-6 Rare fracture of the coronoid process.

are appropriate⁴ in which the condylar processes with the condylus can be freely projected. These images can be specifically supplemented with occlusal images of the maxilla and mandible, angled lateral mandibular images or dental films. In special instances, for example to determine the extent of the dislocation of the mandibular condyle in condylar and capitulum fractures, CT can be used. If CBVI is available, it should be used in preference to CT as it has lower radiation exposure. This does not result in any demonstrable diagnostic disadvantages.

9.2.2 Midfacial Fractures

The midface includes the visceral cranium without the mandible. Midfacial trauma results in typical fracture lines, which makes a uniform classification of midfacial fractures possible. A distinction is drawn between central, centrolateral and lateral midfacial fractures. Central midfacial fractures include Le Fort I/II fractures, naso-orbitoethmoidal fractures, nasal bone fractures and sagittal fractures of the maxilla. The Le Fort III fracture is a centrolateral midfacial fracture. Fractures of the zygomatico-orbital complex, the zygomatic arch and the orbital walls are lateral midfacial fractures.⁵

In addition to the clinical examination, a 3D radiological diagnosis is nearly always required for midfacial trauma, since even a combination of various conventional radiological procedures cannot display all fracture lines. Classical imaging techniques such as that of the paranasal sinuses in an occipitomeatal projection are only useful in basic diagnostics. In addition to visualizing the zygomatic alveolar crest, through which runs the fracture line of many midfacial fractures, radiography of the paranasal sinuses can also provide indirect information regarding fractures, such as a hematosinus or orbital tissue prolapsed into the maxillary sinus (suspended drops). Especially with midfacial fractures, an OPG primarily serves to offer additional evaluation of dentoalveolar structures and the mandible.^{1,2,6}

For the 3D diagnosis of simple midfacial trauma, CBVI should always be preferred over CT, if the former is available. The diagnostic information is equivalent to that of CT, while the radiation exposure is lower. CT is only required in serious midfacial trauma associated with skull and brain trauma, to visualize cerebral structures and exclude traumatic subarachnoidal hemorrhaging and fractures of the cranial vault. At present, a complete image of the frontal sinus can not be reliably produced with CBVI.

Lateral midfacial fractures

The lateral visceral cranium includes the zygomatic arch and the zygomatic process of the frontal bone forming the lateral orbital margin. Since fractures of the zygomatic bone are typically associated with fractures of the infraorbital margin, the orbital floor and the lateral orbital margin, the term zygomatico-orbital complex is used (Figure 9-7). The exposed position of the zygomatic process and the reflexive turning away of the head in the face of frontal dangers explain why fractures of the zygomatic bone are among the most frequent injuries to the visceral cranium. Approximately 25% of all midfacial fractures affect the zygomatic bone/zygomatic arch complex. Among the most frequent causes of accidents are traffic accidents (40%), sports accidents (20%), acts of violence (10%) and falls (10%).⁵

The typical fracture of the zygomatic arch is characterized by a double greenstick fracture with a central depression. This is manifested clinically as a depression in the area of the lateral cheek contour. An additional diagnostic symptom is difficulty opening the mouth, which arises from the restricted mobility of the muscular process of the mandible or from the mechanical constriction of the temporal muscle. Comparative images of the zygomatic arch (so-called "bucket handle effect" images) are diagnostic evidence of this condition. CBVI can also display the zygomatic arch, which is generally dislocated inward.

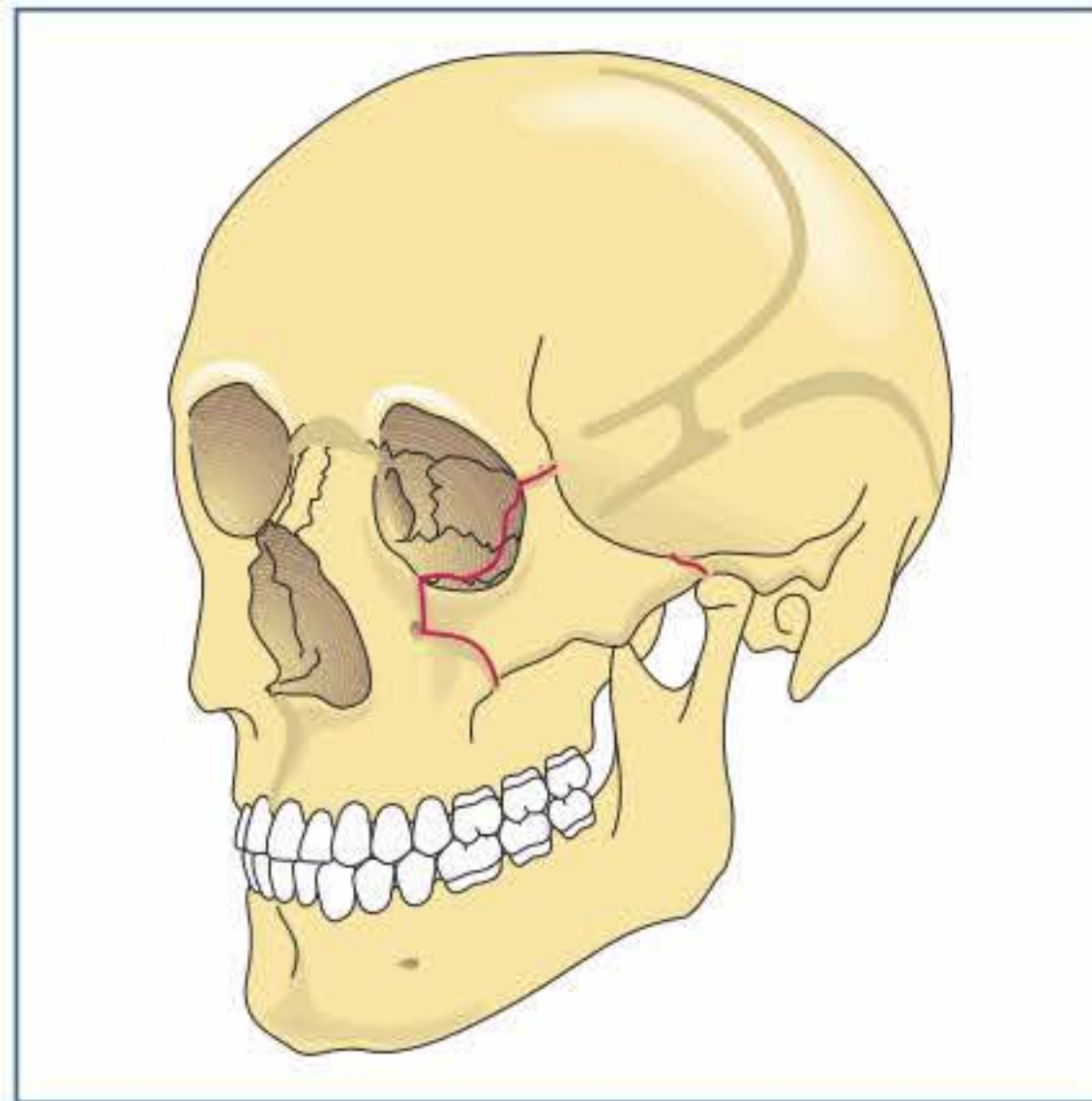


Fig 9-7 Fracture line of a zygomatic bone fracture.



Fig 9-8 Isolated left orbital floor fracture. (a) The orbital contents have prolapsed into the maxillary sinus (hanging drop). (b) During surgery, the prolapsed tissue was placed back in the orbital cavity and supported with a PDS film.

The pathogenesis of isolated orbital wall fractures has not been sufficiently clarified. Under discussion is blunt force on the eyeball, where the resulting force is transferred to the orbital walls ("blow-out mechanism"). However, this should generally cause a fracture of the medial orbital wall. This mechanism does not sufficiently explain the much more common fracture of the more stable orbital floor (Figure 9-8). It is more likely that force acting directly on the infraorbital margin or the facial components of the zygomatic bone deforms the zygomatic bone complex and causes an isolated orbital floor fracture.⁷ Diagnostically indicative are periorbital swelling, monocular hematomas, hyposphagma, enophthalmus, lower eyeball position, disturbances in sensitivity in the area of the infraorbital nerve, restricted eyeball motility and double vision. The two last symptoms result from the constriction of the inferior rectus muscle within the fracture gap. An occipitomental skull radi-

ograph (of the paranasal sinuses) and a selective radiograph of the orbital cavity should be taken for radiological diagnosis. Typical radiological signs are hematosinus, irregularities in the orbital floor and the prolapse of orbital soft tissue into the maxillary sinus ("hanging drop").⁶ When the findings are ambiguous, 3D diagnostics, especially coronal reconstructions, offer maximum diagnostic specificity. If available, CBVI is particularly recommended as it has reduced radiation exposure (Figure 9-8).

Complex zygomatic bone fractures are much more frequent than isolated fractures. The fracture lines run more frequently through three particular areas: the infraorbital margin, the zygomaticoalveolar crest, and the zygomaticofrontal suture. In addition, the zygomatic process is fractured. In approximately 20% of fractures of the zygomatic bone, additional fractures are found in the area of the zygomatic arch. In every instance, the orbital floor is affected, where fractures are rarely linear. More frequently, the entire orbital floor is involved in a comminuted fracture (Figure 9-7).⁵

In addition to the clinical signs of isolated zygomatic arch and orbital floor fracture (see above), the typical symptoms of a zygomatic bone fracture reflect the path of the fracture. For example, osseous steps can frequently be palpated at the three likely fracture areas; furthermore, the inclusion of the infraorbital margin and hence the infraorbital foramen disturb sensitivity in the area of the infraorbital nerve, with hypesthesia to anesthesia in the cheeks, nose, upper lip and the teeth of the affected side.

Diagnostic images of use include the occipitomeatal skull (nasal sinuses), the orbital cavity and axial comparative images of the zygomatic arch ("bucket handle effect").⁶ A combination of several views is always necessary to achieve the required visualization in two planes. Typical radiological signs are hematosinus, step formation at the likely fracture areas and inferiorlateral dislocation of the zygomatic bone. If a CBVI can be taken, multiple classic radiological images are not needed. CBVI is equally as good as CT for the diagnosis of complex zygomatic bone fractures (Figures 9-9 and 9-10).



Fig 9-9 Fracture of the right zygomatic bone. (a) Before surgery, the fractures are well visualized in the region of the facial and dorsal wall of the maxillary sinus, the zygomaticoalveolar crest and the zygomatic bone process. (b) After surgery, the facial maxillary sinus and the zygomaticoalveolar crest are osteosynthetically treated with two microplates. The fracture in the region of the dorsal maxillary sinus still exists.

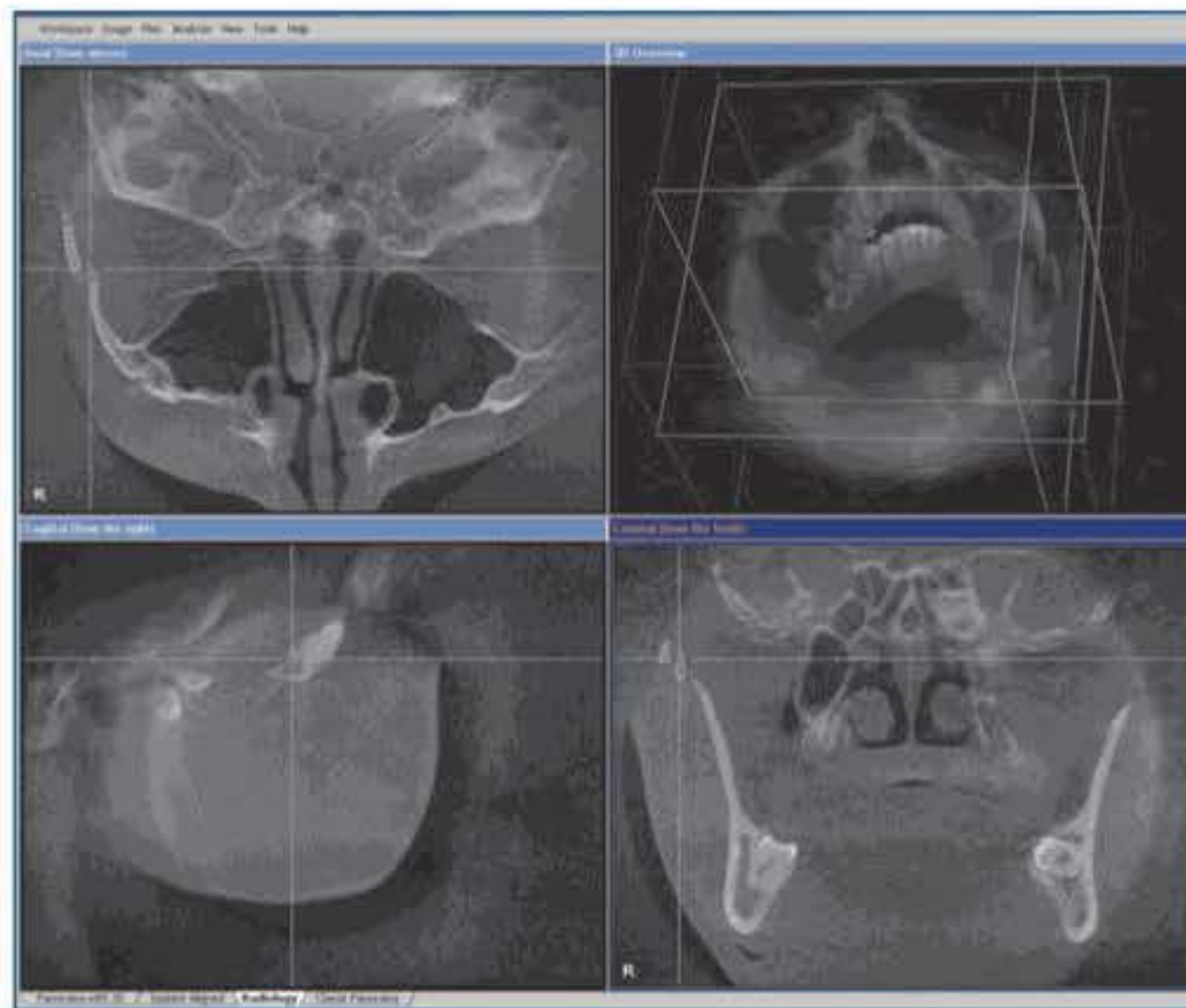


Fig 9-10 Slightly dislocated fracture of the right zygomatic arch with fracture of the right zygomatic arch that are well visualized in the 3D view (view from the cranial side comparable with the zygomatic bone comparative image).

Central and centrolateral midfacial fractures

Central and centrolateral midfacial fractures include Le Fort fractures I–III as well as fractures of the nose skeleton and nasoethmoidal complex.⁵

The typical history for fractures of the bridge of the nose are an impact to the nose area, mobility and crepitation of the nose structure, nasal bleeding, swelling, bilateral periorbital hematoma and obstructed nose breathing. A deformation of the nose can be ambiguous: on the one hand, an observed deformation may have existed before the accident; on the other hand, deformation may have occurred but can be frequently masked by the swelling that develops within the first hours after the accident. Diagnostically, an anterior rhinoscopy is essential to evaluate the condition of the mucosa and the septum. If a septum hematoma is visible, it must be aspirated or removed, since otherwise the septum cartilage may become damaged.

Radiological diagnostics involve x-ray images for soft tissues with a lateral beam path.⁵ However, the physiological bony sutures can easily be confused with fracture lines. In addition, a lateral dislocation cannot be visualized with this imaging technique. CBVI can ideally supplement conventional diagnostics in this context (Figure 9-11).

Le Fort fractures arise from strong, transverse shearing forces on the midface. This classically leads to a basal avulsion of the maxilla from the midface (Le Fort I), a pyramidal avulsion of the maxilla with the nose bone (Le Fort II), or a high avulsion of the entire midface with the maxilla, zygomatic bone and the nose bone (Le Fort III).⁵ The typical paths of the fracture lines are shown in Figure 9.12. Typical accident mechanisms are falls from great heights or impact at high speeds.

The Le Fort classification only serves as a basis for describing central and centrolateral midfacial fractures, which frequently follow an atypical course in clinical practice and are combined with other types of fracture. Accordingly, the clinical symptoms can include all of the signs of fractures

of the visceral cranium listed above. Characteristic of all Le Fort fractures are occlusion disturbances as well as mobility of the maxilla, the central or entire midface (depending on the affected level). Furthermore, depending on the height of the avulsion, bone diastases can be palpated at the zygomaticoalveolar crest, the infraorbital margin or, in the case of Le Fort III fractures, at the lateral orbital cavity. Other typical symptoms are bilateral periocular hematoma and dorso-caudal displacement of the midface ("dish face").



Fig 9-11 Nasal bone comminuted fracture. The fracture is revealed both in the radiological views of the 3D image (a) as well as in a panoramic view with sagittal slices (b).

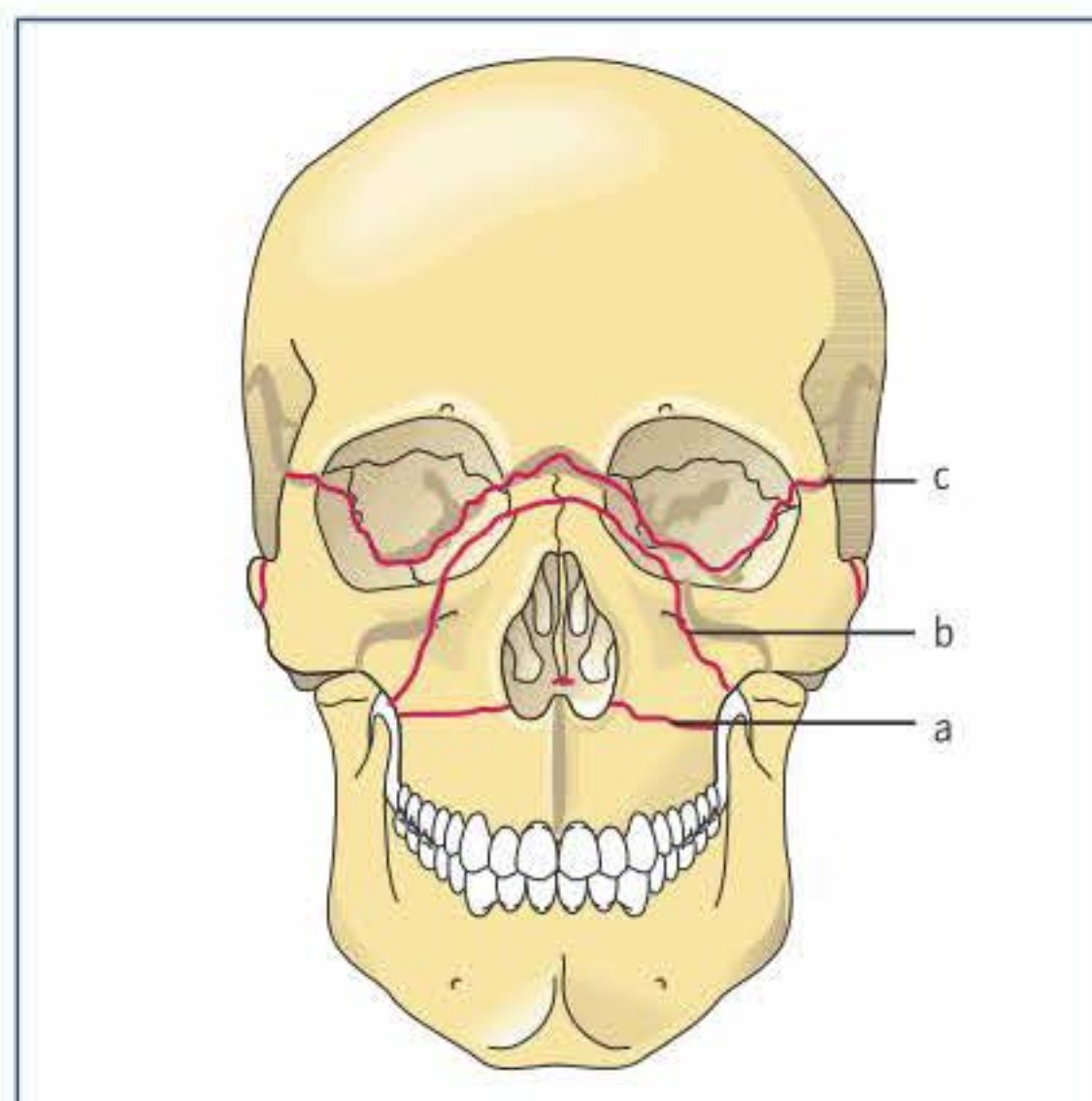


Fig 9-12 Paths of Le Fort fractures:
a, Le Fort I
b, Le Fort II
c, Le Fort III.

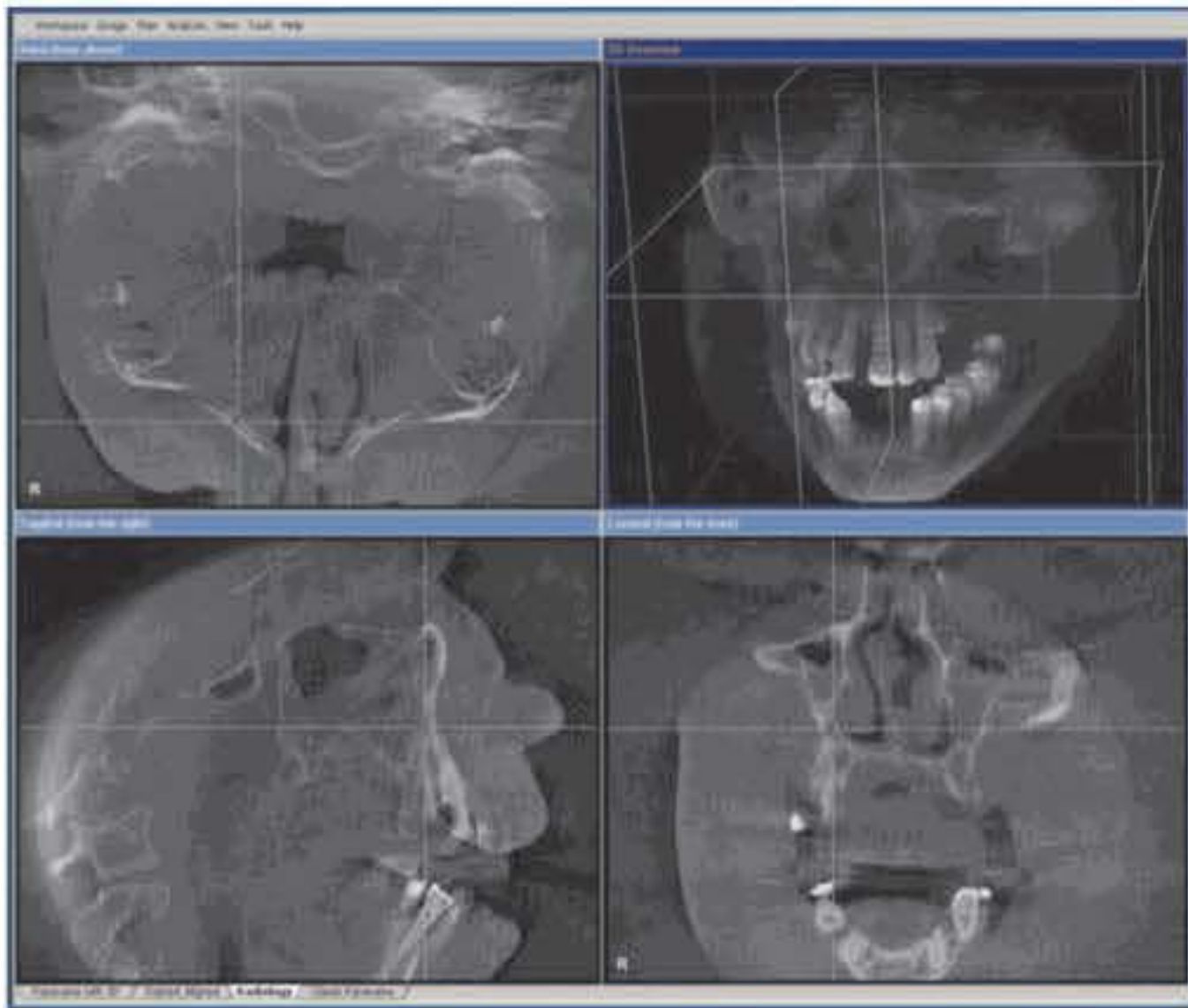


Fig 9-13 Bilateral Le Fort II fracture; the fracture lines in the region of the zygomaticoalveolar crest and the facial and dorsal maxillary sinus walls are revealed.

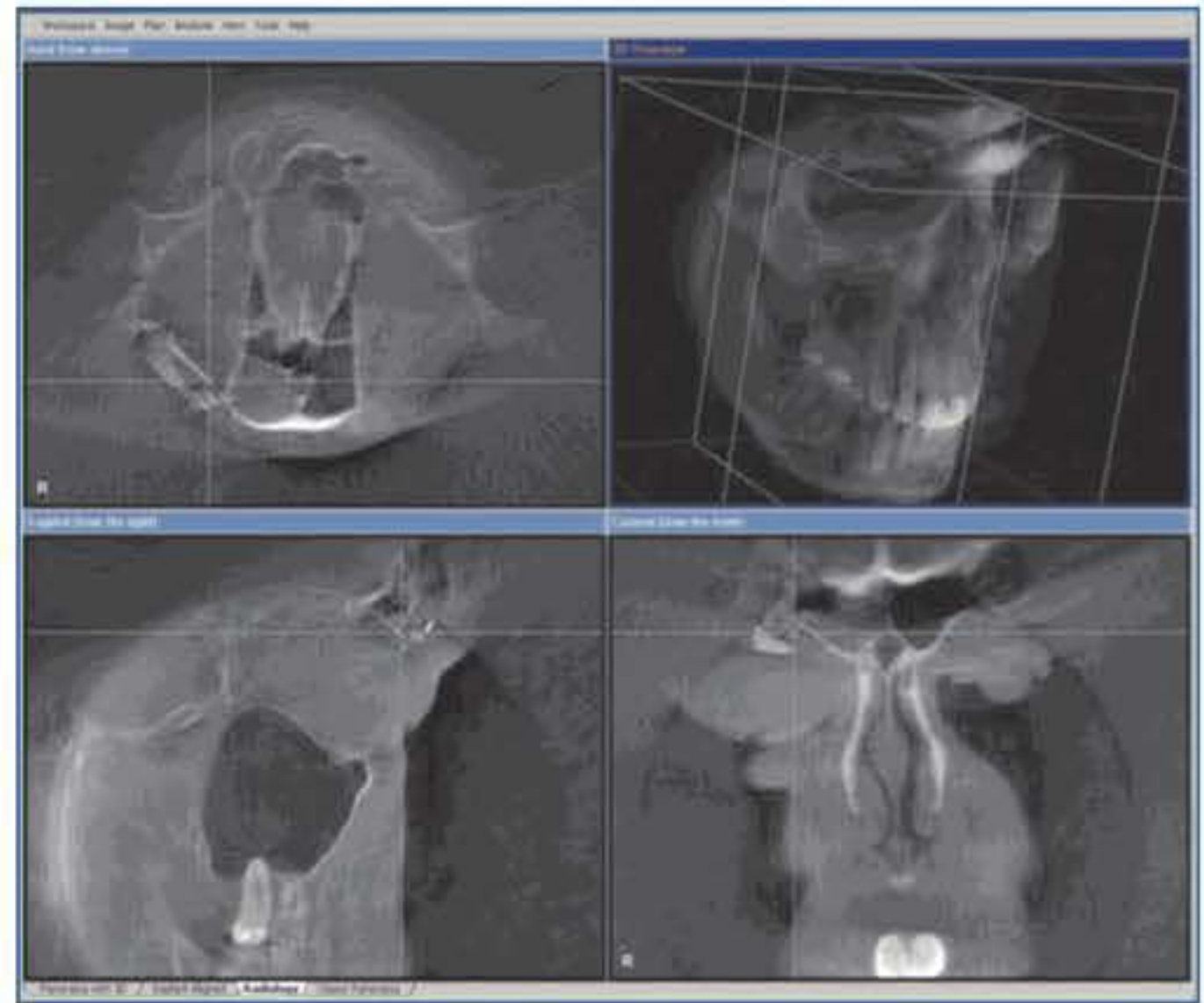


Fig 9-14 Fracture of the right frontal sinus. To portray the region, the patient was positioned approximately 4 cm lower during imaging.

Conventional imaging uses a posterior-mental beam path (paranasal sinus image). Fracture lines can be visualized at the nasal aperture, nasal root, orbital margin, zygomatic arch and the zygomaticoalveolar crest. A hematosinus is usually revealed, providing an indirect sign of a fracture.⁶ Conventional diagnostics can be supplemented by specific radiographs with a different beam path. For example, a zygomatic arch comparative radiograph ("bucket handle effect") and an occlusal radiograph of the maxilla are useful in sagittal fractures of the maxilla. To obtain detailed information, 3D radiological diagnostics are essential. In addition to CT, CBVI is recommended for a comparable image with lower radiation exposure (Figure 9-13).

9.2.3 Fractures of the Frontal Sinus

Fractures of the frontal sinus arise from impact to the lower forehead. Diagnostic symptoms are a visible or palpable depression in the area of the anterior wall of the sinus, as well as sensitivity disturbances in the area of the supraorbital nerve. An axial CT should be taken to exclude frontobasal injury. At present, fractures of the anterior wall of the frontal sinus cannot be reliably visualized with CBVI. Depending on the position of the patient, imaging that is sufficiently precise for planning therapy can be achieved in special cases, so that a CT could be dispensed with (Figure 9-14).

9.3 References

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10 Diseases of the Maxillary Sinus

Robert A. Mischkowski and Philipp Scherer

10.1 Introduction

The maxillary sinus extends as evagination of the nasal cavity into the neighboring bones of the skull, the maxillary bone and zygomatic bone. The individual pneumatization pattern of the maxillary sinus is reached by the age of 14.¹ The connection to the primary nasal cavity (natural ostium) ends in the semilunar hiatus in the middle nasal meatus. The roof of the maxillary sinus is formed by the orbital floor, and the rear wall corresponds to the maxillary tuber. The anterior wall is formed by the facial surface of the maxilla. The floor is close to the roots of the maxillary teeth, somewhat distal to the first premolars.²

Given the high contrast of the pathological processes in comparison with the air-filled lumen and the surrounding bone structures, CBVI is highly suitable for maxillary sinus diagnostics. In radiological diagnostics, particular attention should be paid to pneumatization and the wall contours of the maxillary sinus. Expansive lesions completely or partially obscure the radiolucency of the maxillary sinus. They result in a discernible opacity that can almost always be interpreted as the initial sign of a pathological process. The destruction of the wall contours can be traumatic, inflammatory or caused by neoplasias.

10.2 Anomalies

As organs that developed as a pair, the maxillary sinuses are generally similar in size in one individual. If the size of the maxillary sinus clearly deviates from that expected for a specific age without identifiable current pathological processes, the condition is considered an anomaly. It can be unilateral or bilateral. The following anomalies can be specified:

- aplasia (Figure 10-1)
- hypoplasia (Figure 10-2)
- hyperplasia.

Whereas aplasia of the maxillary sinus is extremely rare,³ hypoplasia has a prevalence of approximately 10%.⁴ When evaluating an anomaly, it must be determined whether the missing or incomplete pneumatization is endogenous or has arisen through secondary processes such as scarring or ossification. One or more septa can be found in 13 to 26.5% of all maxillary sinuses (Figure 10-3).^{5,6} If they completely separate the sinus, mucocèles may develop. In addition, septa are frequently relevant to surgical procedures of the maxillary sinus, such as sinus lifts, since they can complicate the operation. The size of the maxillary sinus and the degree of its pneumatization can be evaluated very well in the orthogonal slices of the CBVI.

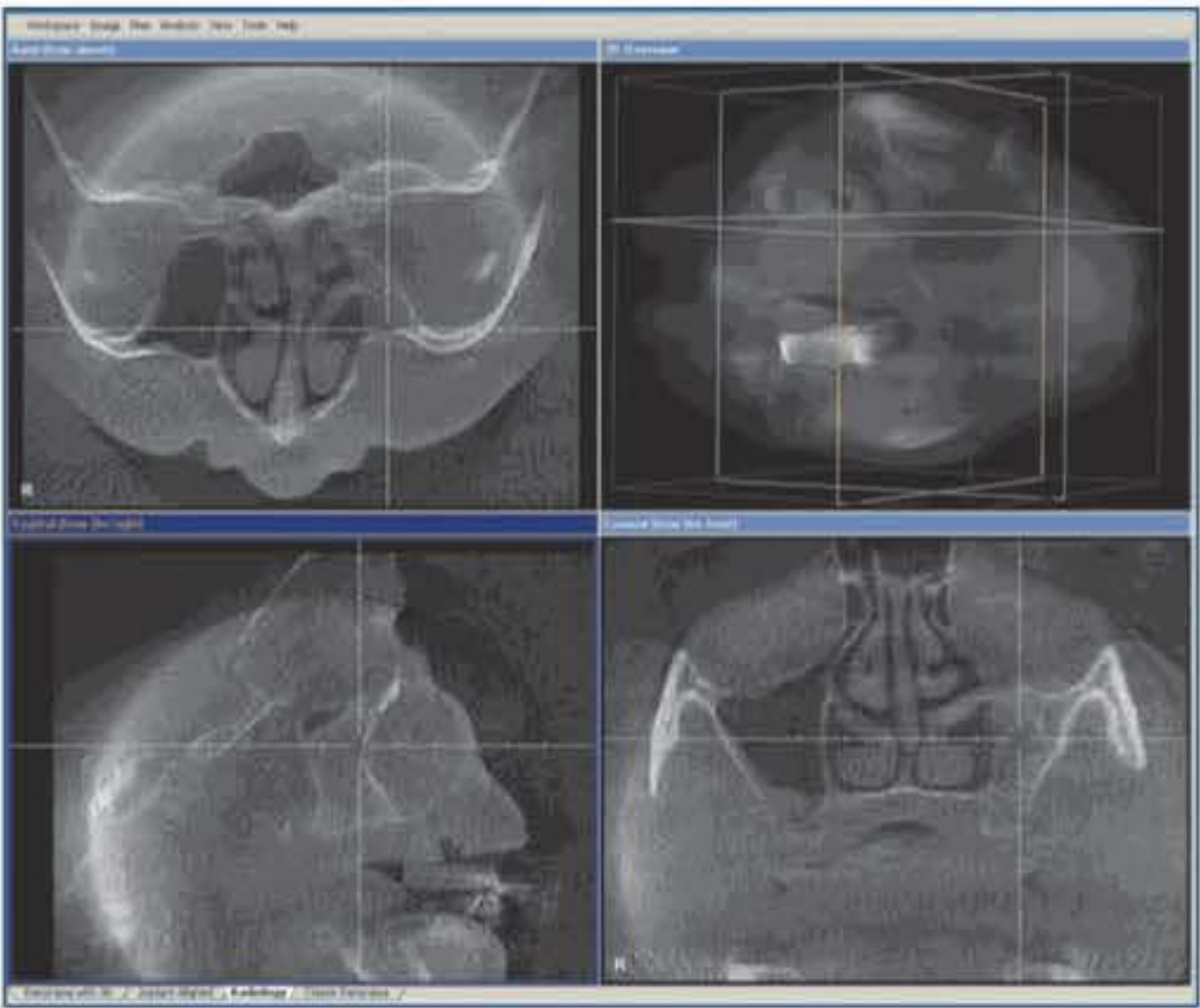


Fig 10-1 Aplasia of the left maxillary sinus as a secondary finding in a 68-year-old male.



Fig 10-2 Asymptomatic hypoplasia of the right maxillary sinus in a 71-year-old female.

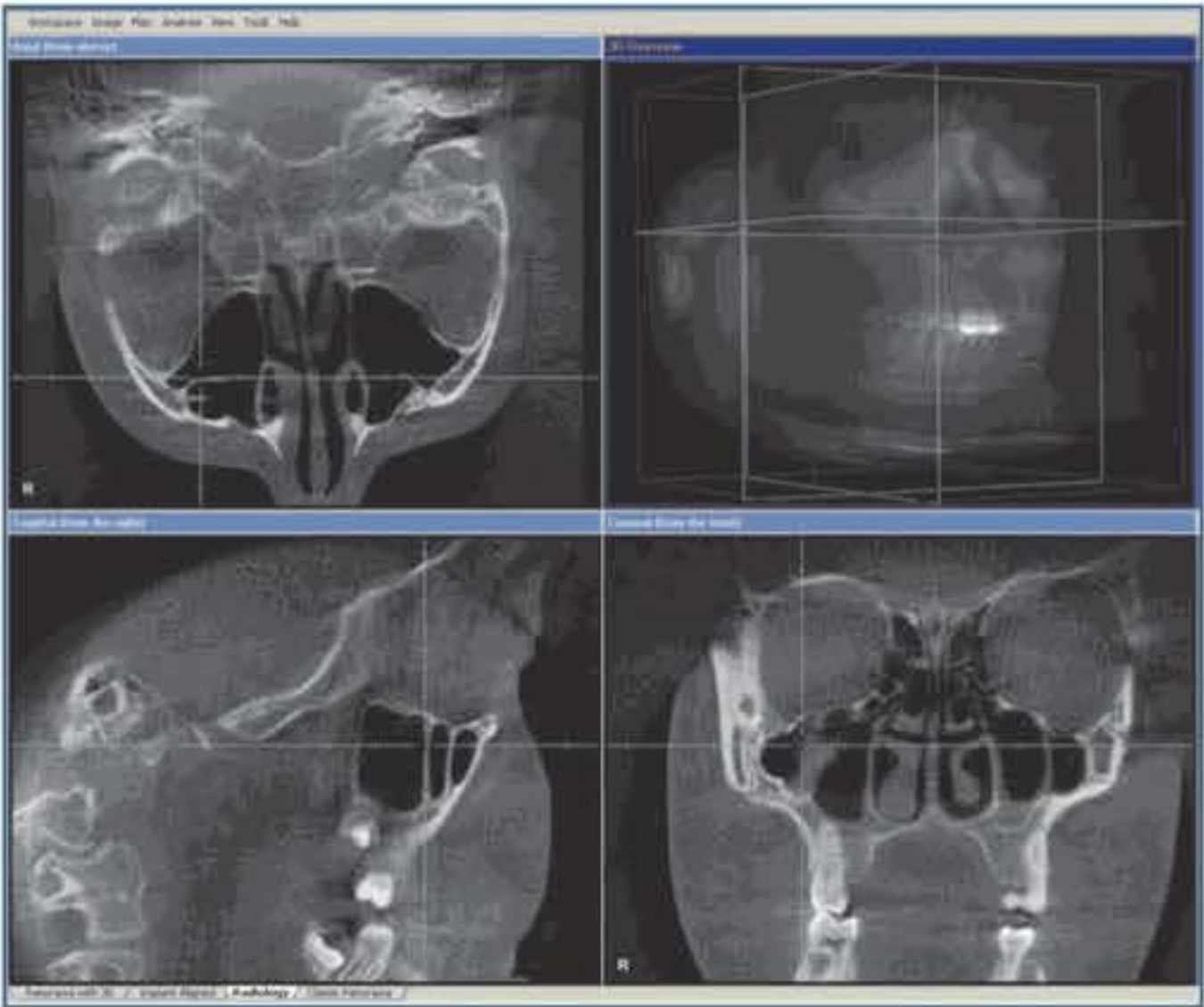


Fig 10-3 Septation of the maxillary sinuses, especially on the right side, in a 15-year-old female.



Fig 10-4 Right maxillary sinus filled with a purulent secretion in acute odontogenic maxillary sinusitis in a 52-year-old female. Apical periodontitis at tooth 16 can be identified as the cause.

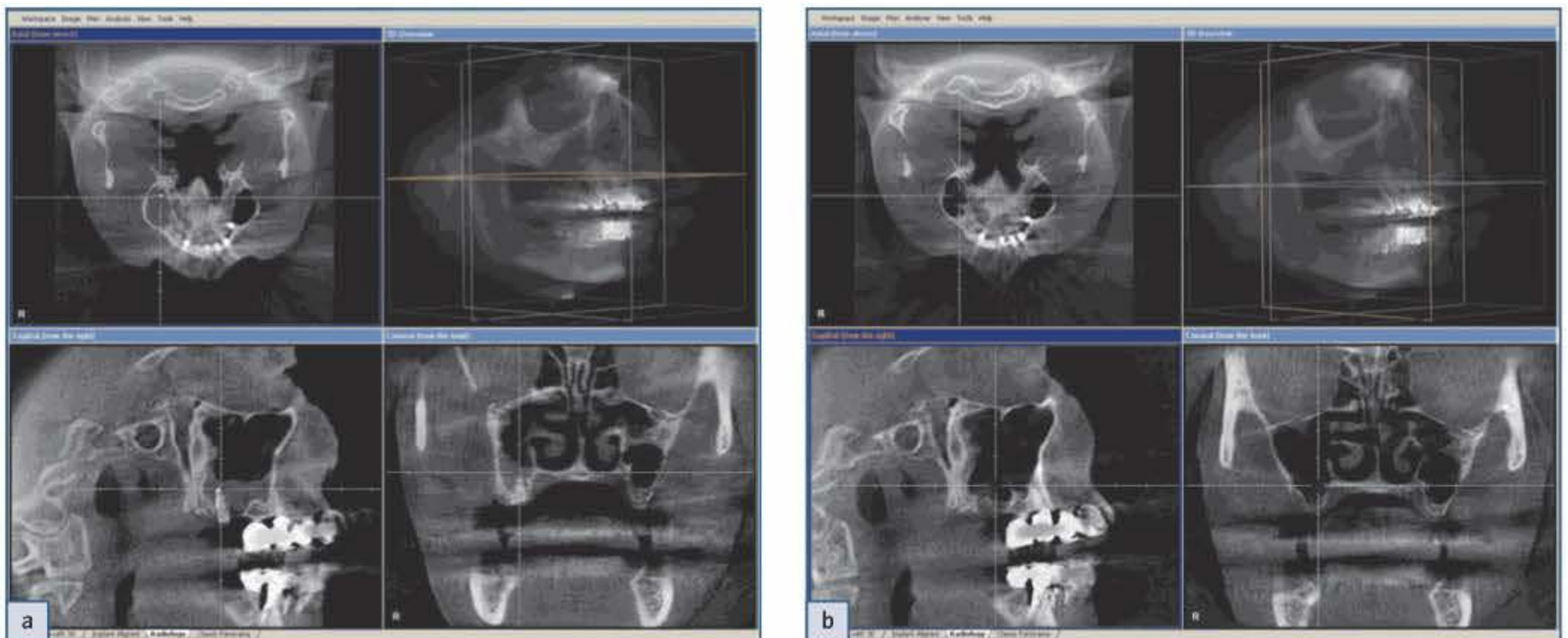


Fig 10-5 Oroantral fistula with acute odontogenic right maxillary sinusitis. (a) One week after extraction of tooth 17 in a 71-year-old woman, the iodoform-soaked gauze strip in the socket of the extracted tooth can be seen to extend into the maxillary sinus. (b) Ten days after closure of the oroantral fistula and antibiotic therapy, the maxillary sinus is largely bland and well ventilated.

10.3 Maxillary Sinusitis

Maxillary sinusitis can have odontogenic or rhinogenic causes. Odontogenic maxillary sinusitis develops from apical periodontitis (Figure 10-4), oroantral fistulae after tooth extraction (Figure 10-5), advanced marginal periodontitis, or an infected cyst arising from teeth adjacent to the maxillary sinus. An odontogenic etiology is found in approximately 10 to 12% of all sinusitides.⁷ Primary rhinogenic sinusitis is usually transferred from the nasal cavity. It can result from viral or bacterial rhinitis, a mechanical ventilation disturbance such as a pronounced septum deviation, or an allergic reaction. Depending on the clinical course, a distinction is drawn between acute and chronic forms.



Fig 10-6 Chronic non-odontogenic left maxillary sinusitis in a 60-year-old woman. (a) The maxillary sinus is almost completely filled with polypoid hyperplastic tissue. (b) The OPG reconstruction reveals a close relationship between the roots of tooth 27 and the maxillary sinus floor, but no apical lesions as the possible cause of the disease.

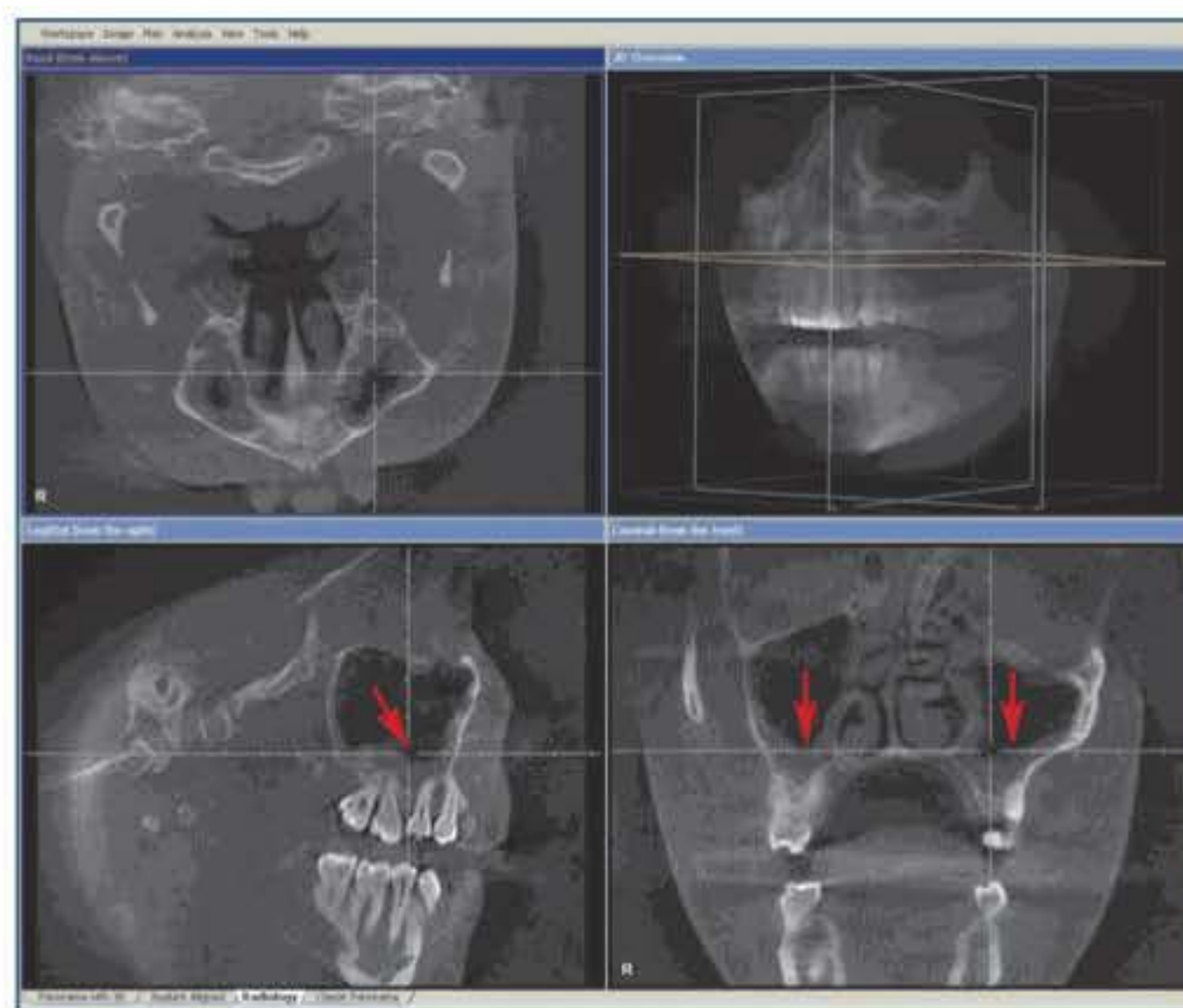
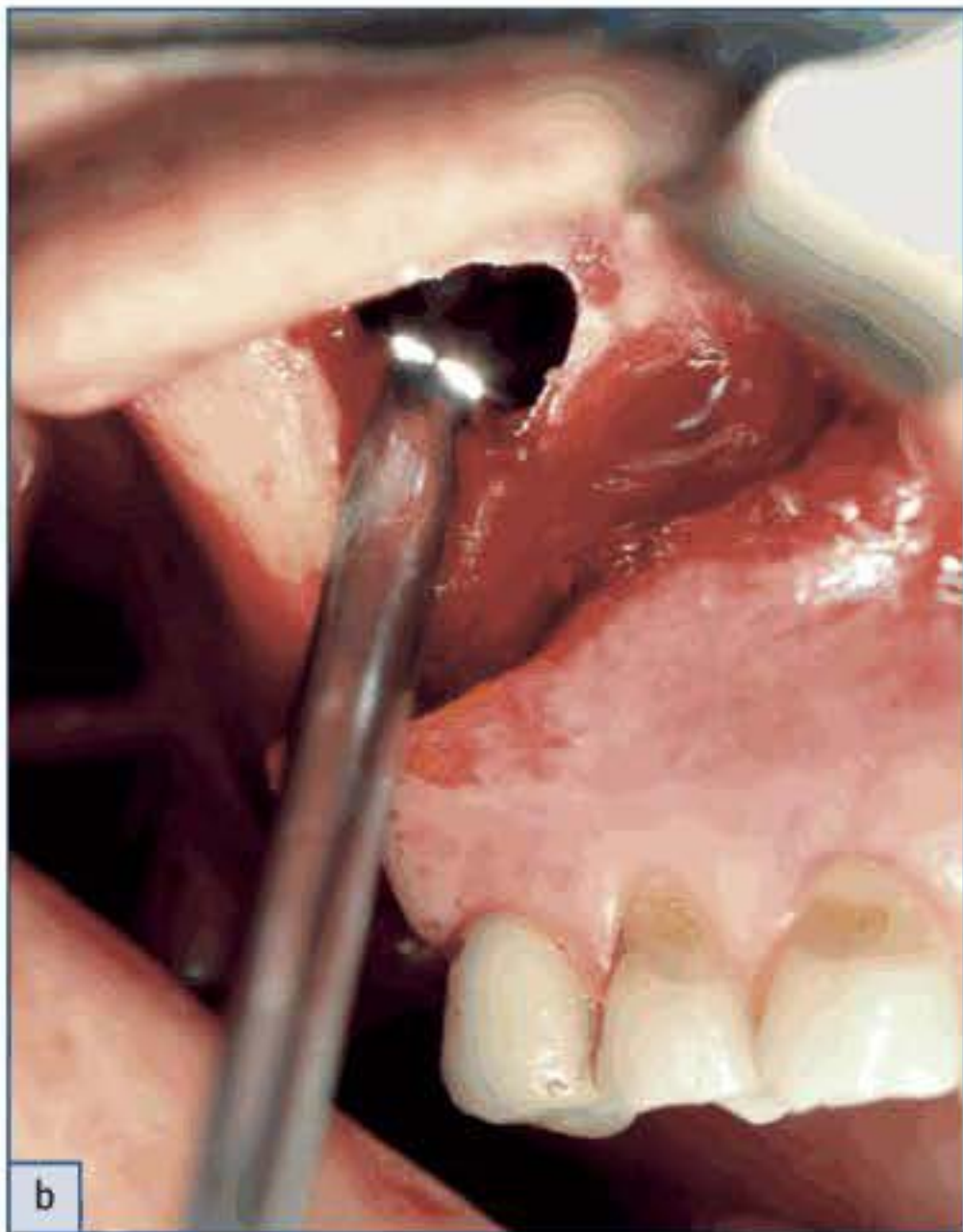
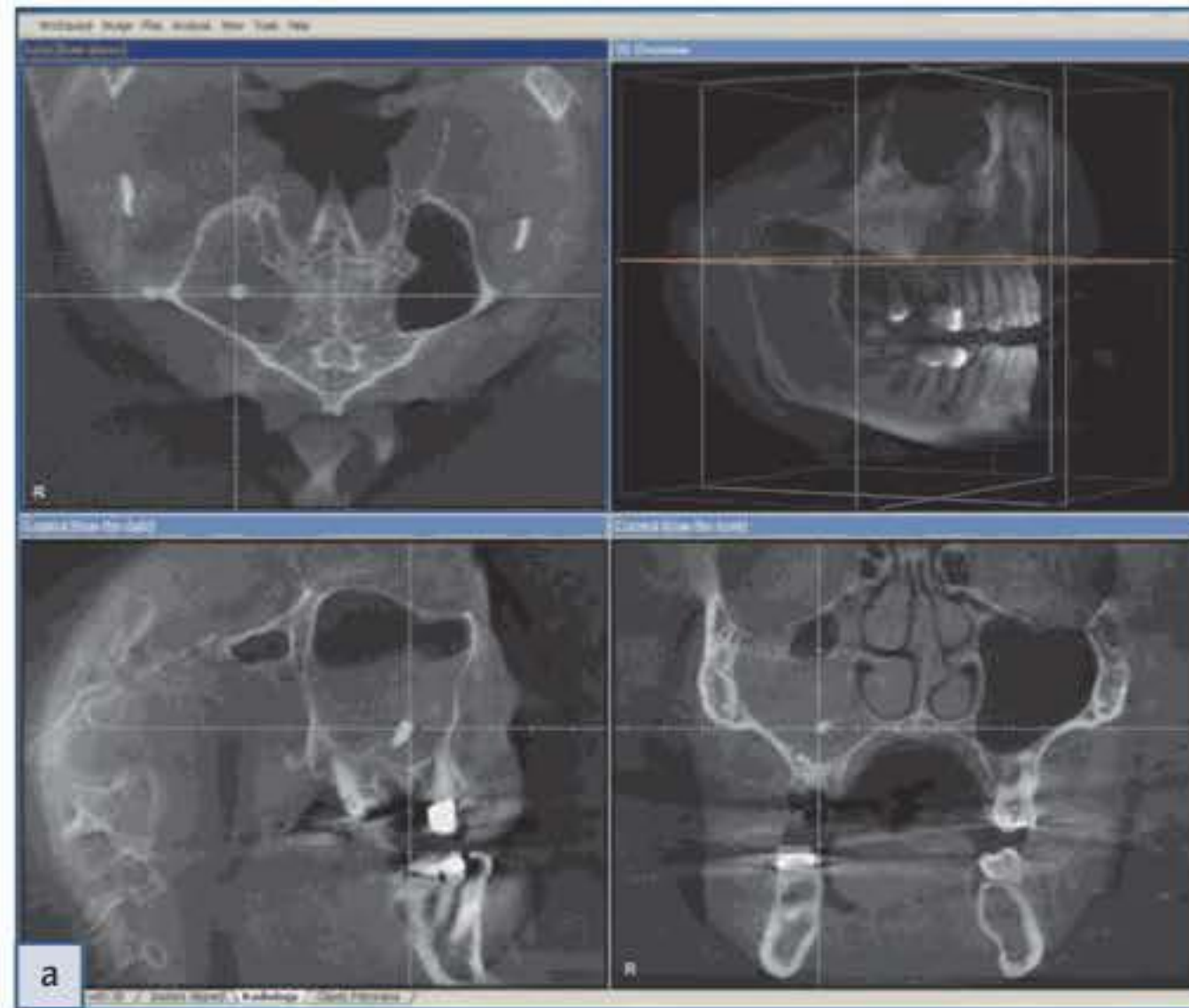


Fig 10-7 Basal garland-shaped mucosa pad in both maxillary sinuses as a sign of allergy-related maxillary sinusitis in a 29-year-old female.

In the acute phase, it must be borne in mind that the clinical situation is always somewhat ahead of the radiological findings. The directional movement of the cilia is inhibited by damage to the respiratory epithelium; consequently, the first identifiable symptom is opacity of the maxillary sinus caused by retention of secretions.⁸ This is followed by a seropurulent accumulation of fluid that appears as a smooth surface in the radiograph and is termed “air-fluid level”.

A chronic course is characterized by marginal hypertrophy of the mucosa and the formation of solitary polyps or polyp-like structures, which may totally obstruct the lumen (Figure 10-6). Garland-shaped mucosal pads with involvement of the nasal cavity indicate an allergic origin for sinusitis (Figure 10-7).⁹

Fig 10-8 Sinusitis caused by a foreign body. (a) A fractured root has luxated into the right maxillary sinus after extraction of tooth 16 in a 52-year-old male. Partial opacity of the maxillary sinus with air-fluid level is a sign of acute concomitant sinusitis. (b) Sinusoscopic removal of the root via an osteoplastic access through the facial maxillary sinus wall. The bone fragment temporarily removed to create an access window will be subsequently repositioned and fixed with absorbable sutures. (c) The dislocated root removed from the maxillary sinus.



10.4 Foreign Bodies

Foreign bodies can enter the maxillary sinus through trauma or dental and surgical manipulation. Iatrogenically introduced foreign bodies are generally teeth or tooth fragments (Figure 10-8), implants (Figure 10-9), impression substances, filling material or dislocated augmentation material after a sinus graft.¹⁰ Glass and wood splinters as well as metal fragments can enter the maxillary sinus during traumatic events.¹¹

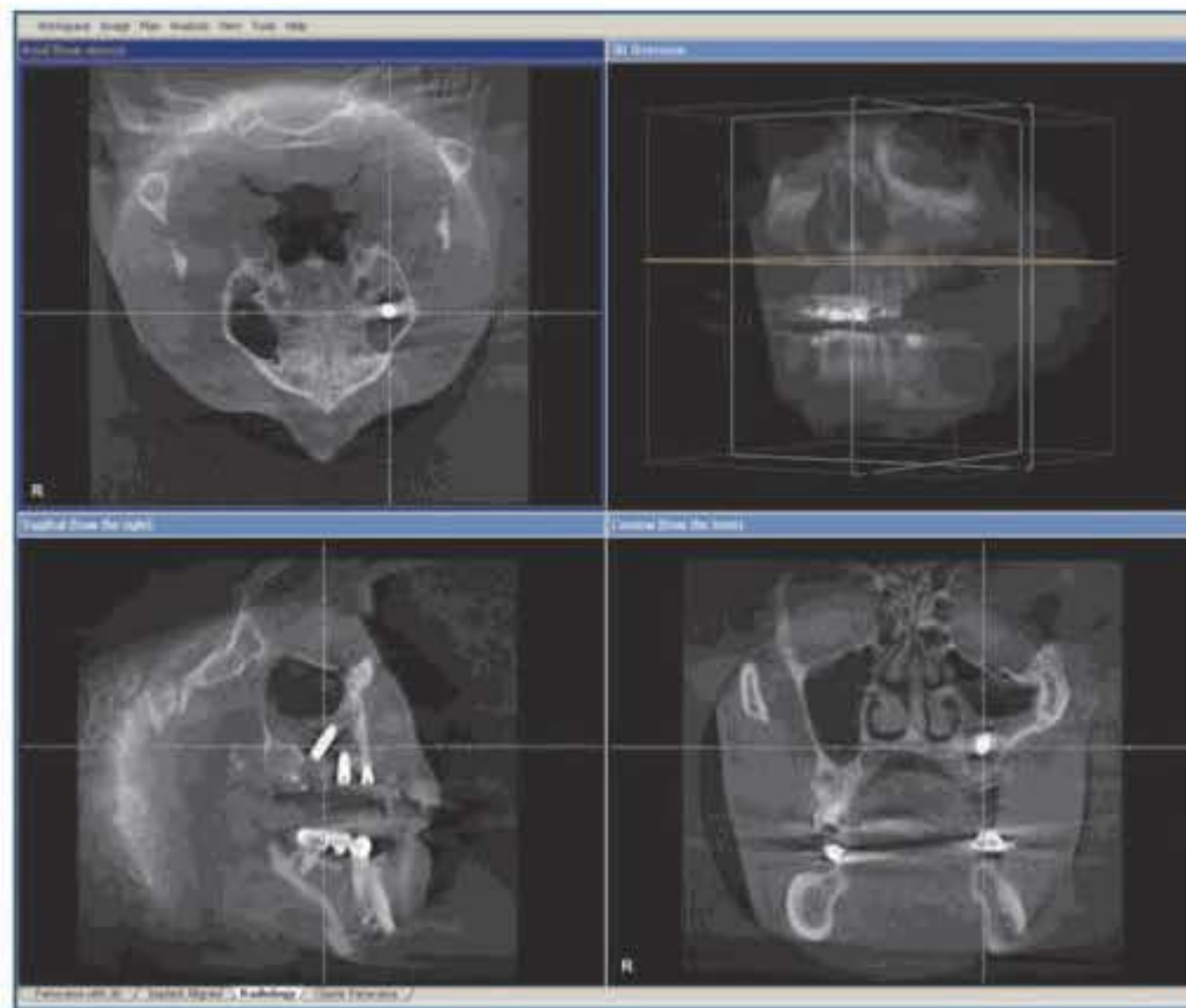


Fig 10-9 An implant that has luxated into the left maxillary sinus in a 43-year-old male.

Foreign bodies that are not radiolucent can be easily located using CBVI. It must be determined if the foreign body is lying freely in the maxillary sinus or if it is located beneath the mucosa. In addition, the spatial relationship to the walls of the maxillary sinus must be analyzed (basal, lateral, posterior, etc.). If the radiological assessment does not immediately follow the event that led to the foreign body entering the maxillary sinus, and a few days have passed, inflammatory processes can significantly complicate the diagnosis by obscuring the foreign body. In the long term, chronic inflammation can cause scarring and cystic changes in the mucosa, with destruction of the osseous walls.

10.5 Cysts

The most frequent cysts formed in the maxillary sinus are mucosal retention cysts, affecting 10 to 35% of all patients with maxillary sinusitis.¹² The cysts arise either from the obstruction of the duct of a mucous gland in the sinus mucosa or by the collection of serous secretions in the subepithelial mucosa layers. In the first (mucinous retention cyst), the cyst wall consists of duct epithelium or gland capsule; in the second (serous retention cyst), it consists of elevated sinus mucosa. This cystic change, which is diagnosed in many cases as an asymptomatic secondary finding, is characterized by a smoothly delimited, single or multilocular spherical opacity in the maxillary sinus lumen. It frequently arises in the basal areas of the maxillary sinus and is often caused by inflammatory processes at the adjacent teeth (Figure 10-10).

Retention cysts of the maxillary sinus are often incorrectly equated with mucocoeles. A mucocoele develops as an occlusion cyst upon the obstruction of the natural ostium or of a compartment of the maxillary sinus. Like a retention cyst, it also consists of mucinous secretion surrounded by an epithelial layer. A characteristic radiological feature of retention cysts is that a residual lumen of the maxillary sinus remains, even when the cyst is very large. In addition, the osseous margins of the maxillary sinus are not affected. In contrast, genuine mucocoeles can completely occlude the lumen and, in advanced stages, displace the osseous walls and eventually destroy them through pressure atrophy.^{13,14}



Fig 10-10 Large, bilocular retention cyst of the left maxillary sinus in a 23-year-old male, appearing as a well-delineated, spherical radiopaque lesion located at the base of the sinus.

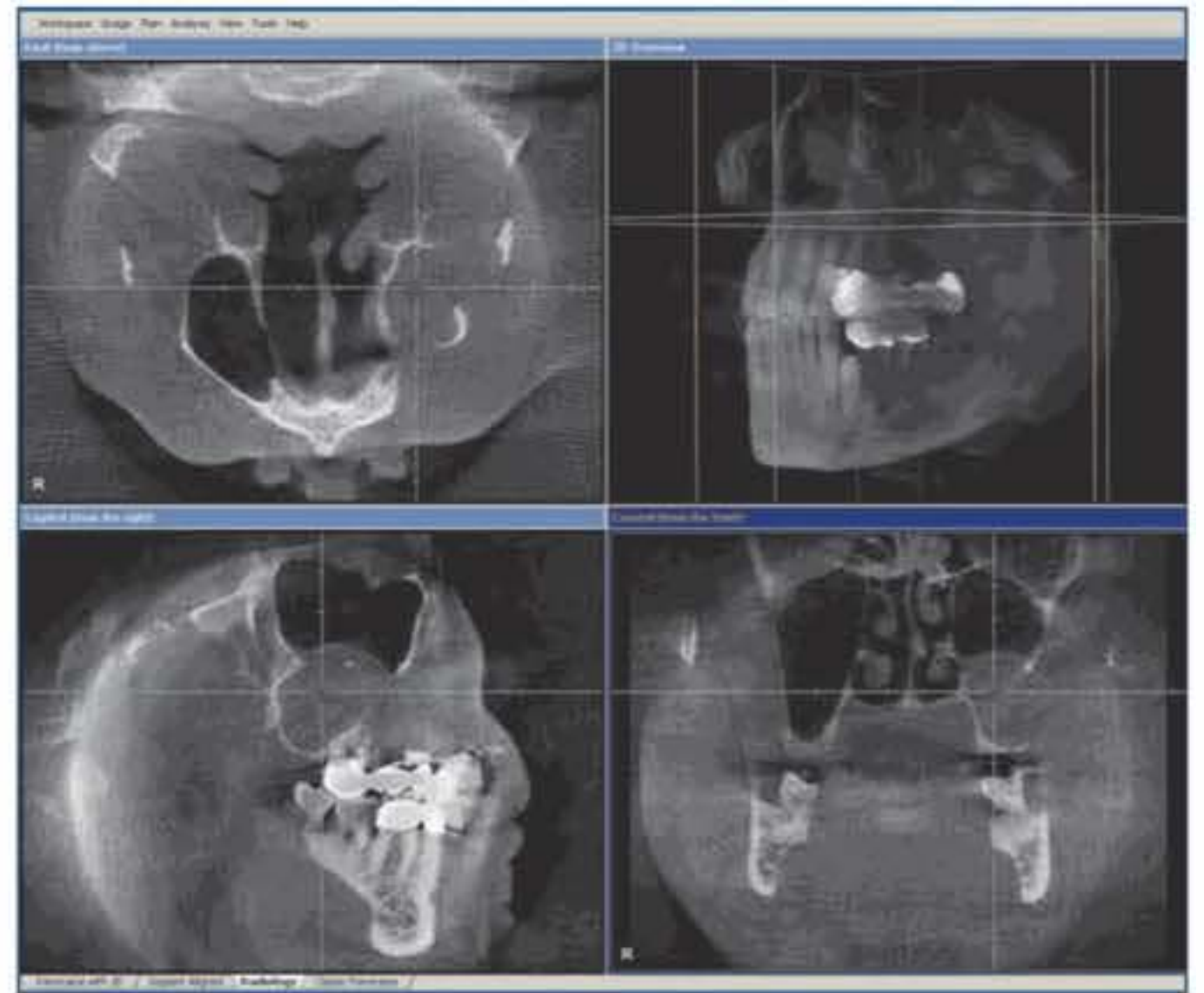


Fig 10-11 Radicular cyst of the left maxillary sinus originating from devitalized tooth 27 with chronic apical periodontitis in a 62-year-old male.



Fig 10-12 Large follicular cyst of the right maxillary sinus in a 19-year-old female. The cyst extends from the ectopic tooth germ located at the posterior wall of the maxillary sinus.

Odontogenic cysts can arise from the teeth of the posterior maxilla and grow into the lumen of the maxillary sinus. These primarily include radicular and follicular cysts. According to the most recent classification of the World Health Organization (2003),¹⁵ cysts previously termed keratocysts are currently identified as keratocystic odontogenic tumors and now belong to the group of benign neoplasias (see Chapter 5). Odontogenic cysts are identifiable as round, radiopaque lesions discernible against the lumen of the maxillary sinus.¹⁶ When they are large, they displace or destroy the maxillary sinus walls and are separated from the lumen by a thin bone layer (Figure 10-11). Follicular cysts have a direct spatial relationship with a tooth germ. Often, an ectopic tooth germ can be diagnosed in the cyst (Figure 10-12).

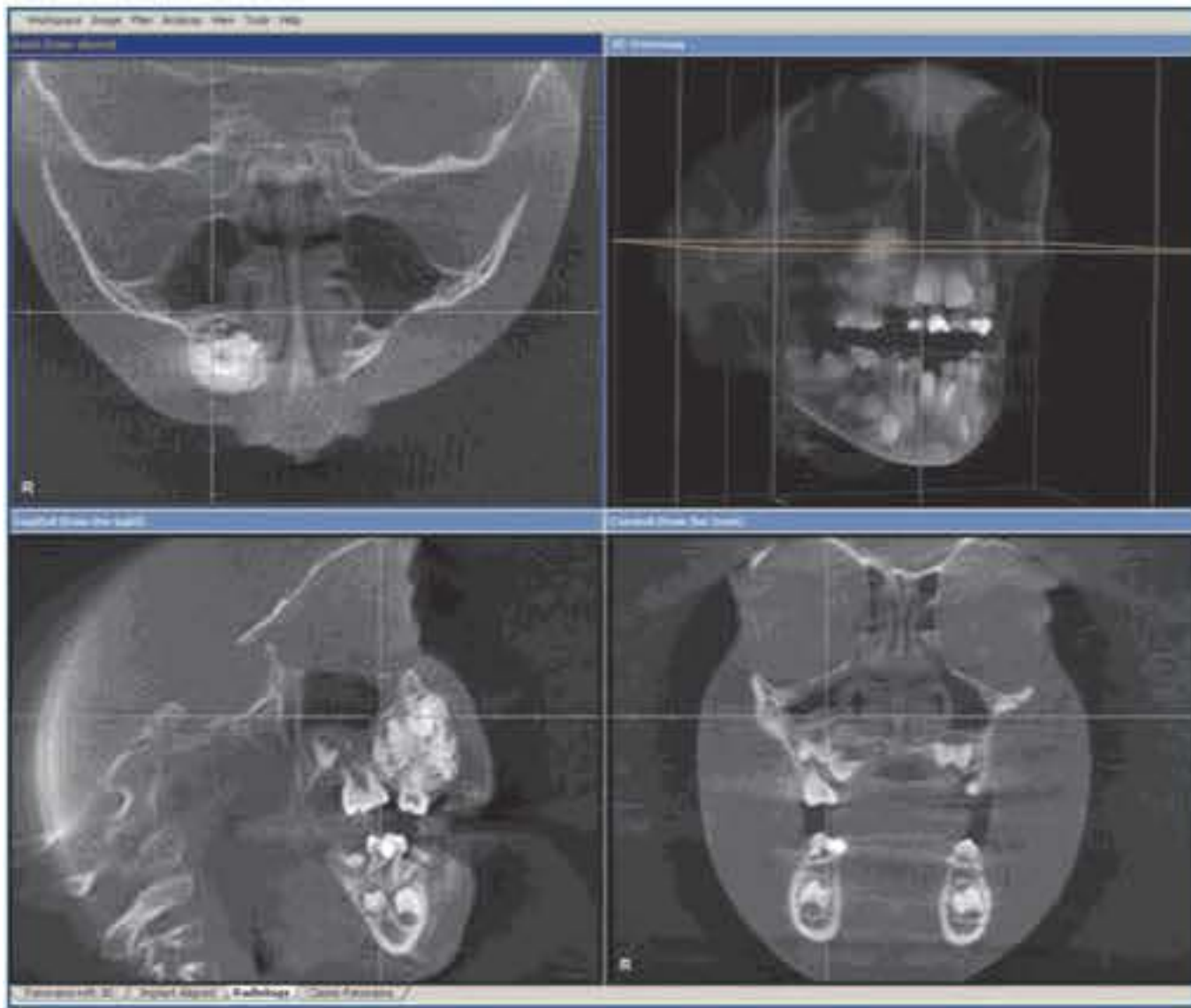


Fig 10-13 Expansion of a compound odontoma of the right maxilla into the lumen of the maxillary sinus in a 6-year-old boy. The image reveals the characteristic inhomogeneous opacity, with enclosed tooth germs surrounded by a zone of radiolucency.

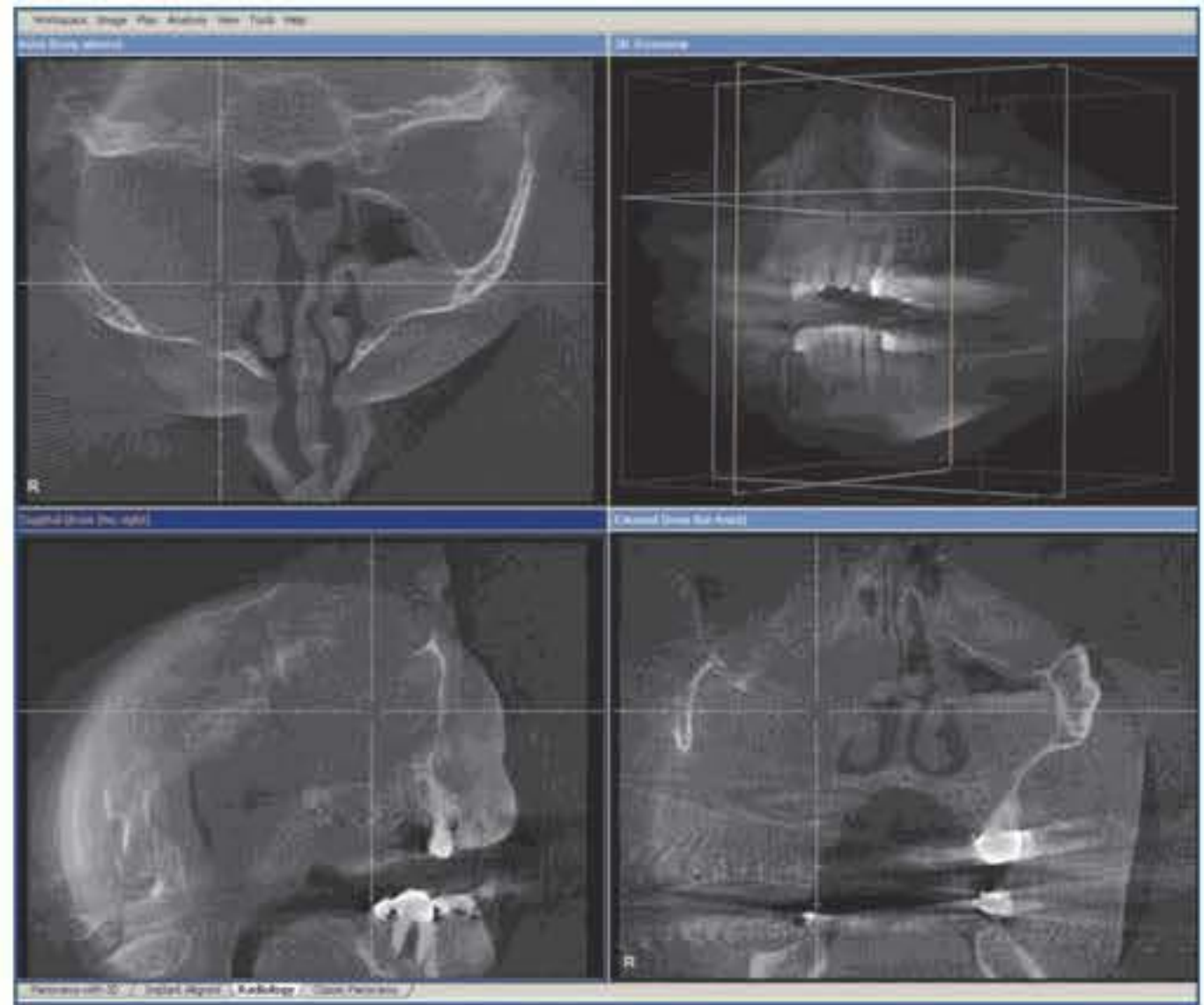


Fig 10-14 Extensive squamous cell carcinoma of the right maxillary sinus in a 72-year-old male. The image reveals the complete destruction of the lateral and posterior maxillary sinus wall, the infiltration of the orbital floor, as well as an invasion in the right nasal cavity. Concomitant chronic sinusitis is found on the left side.

10.6 Tumors and Tumor-like Diseases

Benign and malignant neoplasias in the posterior region of the maxilla expand relatively quickly into the maxillary sinus. Conversely, masses originating in the maxillary sinus can penetrate the alveolar process and appear as lesions of the maxilla or the oral mucosa. Among the most common benign tumors in the maxillary sinus are osteomas, ossifying fibromas and odontogenic neoplasms such as keratocystic odontogenic tumors, ameloblastomas, odontomas (Figure 10-13) and cementifying fibromas (Chapter 5). Between 50% and 80% of all malignant diseases of the maxillary sinus are squamous cell carcinomas (Figure 10-14).¹⁴ The remainder include adenocarcinoma, adenoid cystic carcinoma, lymphoma and osteosarcoma. Metastases of tumors from other locations occur much rarer than in the mandible.¹⁷

In addition to malignant neoplasms, tumor-like bone disease such as fibrous dysplasia can be observed in the region of the maxillary sinus. The maxilla is the bone most frequently affected by craniofacial fibrous dysplasia, and the lesion almost always expands into the maxillary sinus (Figure 10-15).¹⁸

The predominant radiological criterion is the destruction of bone and opacification of the maxillary sinus, as well as displacement of the eyeball or the infiltration of the orbita once a certain size is reached. The growth of benign tumors causes pressure atrophy of the bone. The destruction pattern results in regular well-delineated bony margins of the lesion. Malignant tumors typically manifest aggressive, infiltrating growth, which leads to an irregular, poorly delineated destruction of the osseous boundaries of the maxillary sinus.^{19,20}

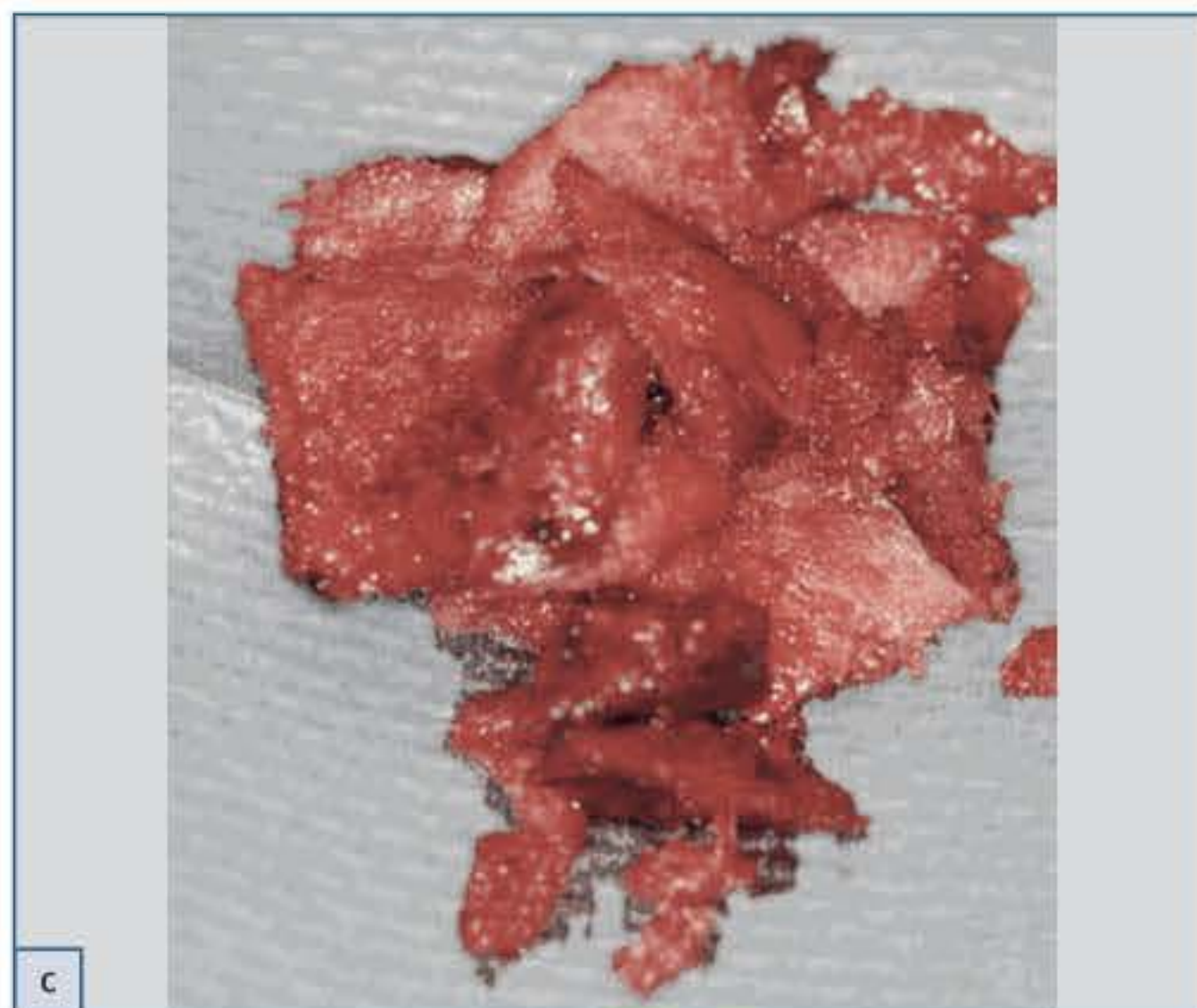
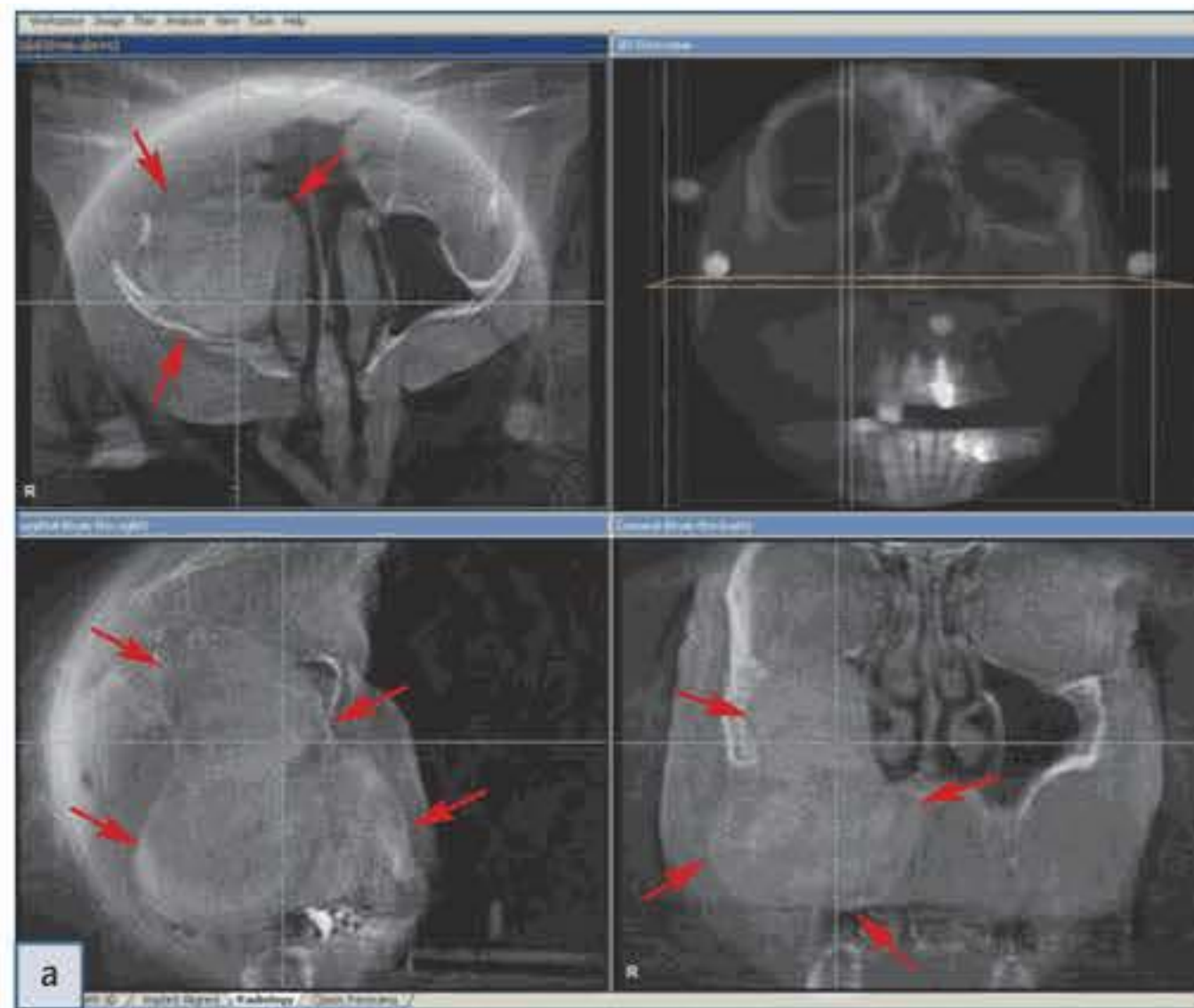


Fig 10-15 Massive fibrous dysplasia of the right maxilla with complete obstruction of the maxillary sinus in a 74-year-old male. (a) The lesion is relatively homogeneous and less radiopaque than normal bone owing to the large amount of connective tissue. (b) Intraoperative view of the right maxilla after the mucoperiosteal flap is elevated. An osteotomy is performed in order to remove the excess dysplastic bone. (c) Resected dysplastic bone. It is soft and interwoven with connective tissue.



Fig 10-16 Isolated fracture of the zygomaticoalveolar buttress in a 62-year-old female. Hematosinus and bone displacement are revealed in the laterofacial wall structures of the maxillary sinus.

10.7 Trauma

The walls of the maxillary sinus can also be affected in a number of midfacial fractures. They generally include central midfacial fractures on the level of Le Fort I and Le Fort II, as well as centro-lateral midfacial fractures on the level of Le Fort III. Furthermore, the maxillary sinus is always involved in fractures of the zygomatico-orbital complex and isolated orbital floor fractures. Fractures of the nasal bones and maxilla can also involve the maxillary sinus.

An important radiological criterion is the partial or total opacity of the lumen from traumatic hemorrhaging, so-called hematosinus (Figure 10-16). If the maxillary sinus is only partially filled, a characteristic air-fluid level appears. The fracture lines within the maxillary sinus walls are very easy to evaluate by CBVI, and the type of fracture and seriousness of injury are usually very easy to assess.

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11 Diseases of the Salivary Glands

Robert A. Mischkowski and Philipp Scherer

11.1 Introduction

The salivary glands of the oral cavity include the paired large salivary glands (i.e. the parotid, submandibular and sublingual glands) plus numerous small glands in the lips, tongue, cheek and soft palate. In CBVI basic images, the salivary glands are not visualized. Among the pathological changes, only stone formation and cysts can be diagnosed after they reach a certain size. Diseases such as tumors, sialadenitis of various etiologies and sialadenosis remain the domain of imaging procedures such as MRI, sonography, scintigraphy and sialography.¹

11.2 Sialolithiasis

Sialoliths are primarily found in the excretory ducts of the large salivary glands, Wharton's duct (submandibular gland) and Stensen's duct (parotid gland) (Figure 11-1). Their occurrence in the glandular parenchyma is significantly less common.² In 80 to 90% of those with sialolithiasis, the submandibular gland is affected, where 85% of all stones arise in the excretory duct.³ Most cases involve single stones. Most sialoliths occur singularly but multiple stones are diagnosed approximately 25% of the time.

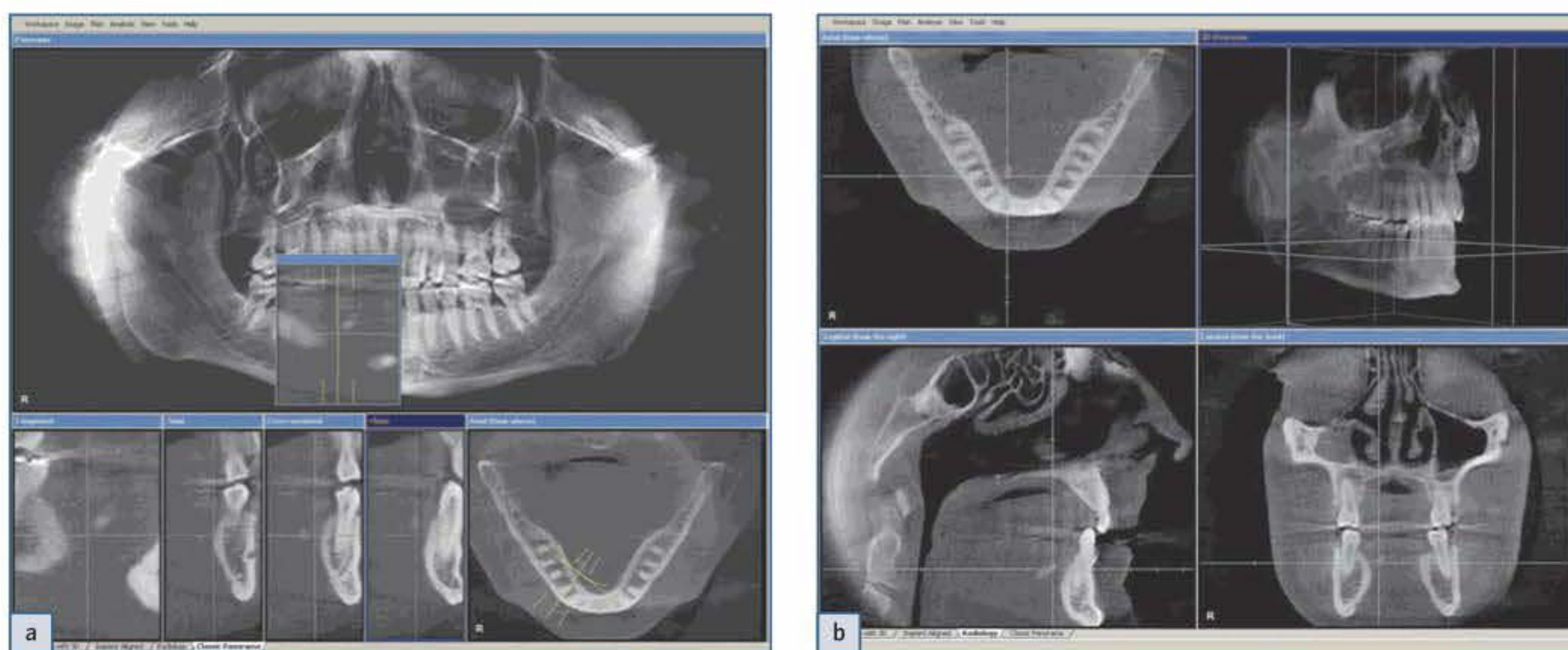


Fig 11-1 The use of CBVI shows a sialolith in the right Wharton's duct in a 39-year-old male. The stone generated acute sialadenitis with submandibular swelling, redness and elevation of the right oral floor as well as pus exiting the right caruncula.



Fig 11-2 In the sonograph, the stone appears as an echogenic, elongated structure with an acoustic shadow.

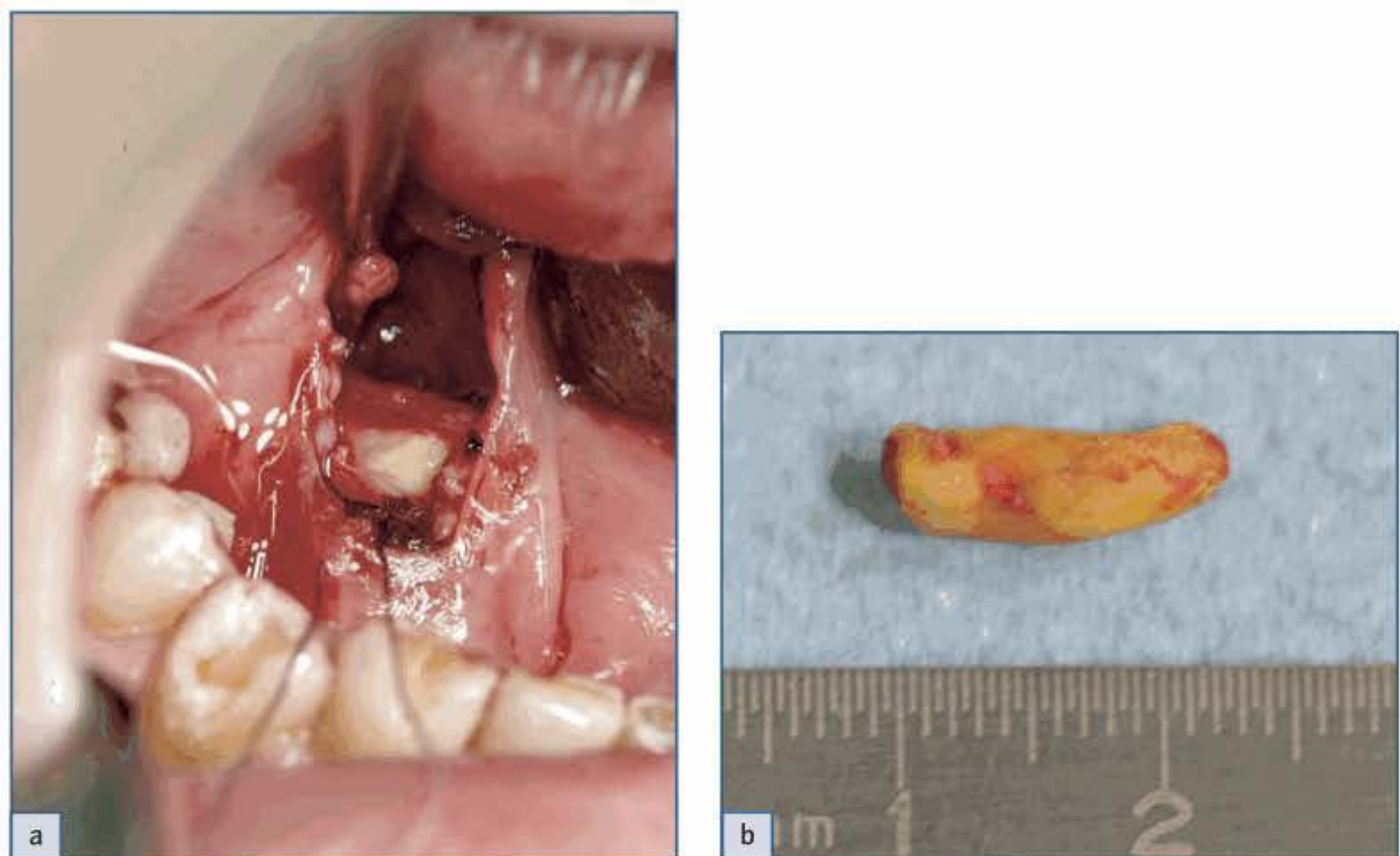


Fig 11-3 Treatment for a sialolith in the right Wharton's duct (see Figs 11-1 and 11-2). (a) The intraoperative view, with the duct opened and the stone exposed. (b) The removed stone.

The stones appear as round or oval, homogeneous, relatively sharply delimited structures in the radiographic image. Between 10% and 20% of all stones are radiolucent^{3,4} and cannot be diagnosed by CBVI. If they can be radiologically visualized, CBVI will provide the exact position of the stones, making this technique clearly superior to conventional x-ray projections. If sialolithiasis is clinically suspected but cannot be demonstrated radiologically, imaging procedures such as sonography and MRI are recommended (Figure 11-2). The value of conventional sialography in the diagnosis of sialolithiasis is controversial and it should be reserved for chronic sialadenitis.⁵ In particular, non-invasive MR sialography with heavily T₂-weighted sequences has proven successful in the visualization of the duct system of the salivary glands.^{6,7} After it has been precisely located, the sialolith can be surgically removed (Figure 11-3).

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12 Diseases of the Temporomandibular Joint

Philipp Scherer and Jörg Neugebauer

12.1 Pathology of the Temporomandibular Joint

Diseases of the temporomandibular joint can affect different anatomical structures and hence different tissues. In contrast to most other diseases of the maxillofacial region, a wide variety of imaging procedures can be used to visualize the affected structures.

Radiological techniques will portray osseous structures. Simple transcranial images do not have a very important role in the diagnosis of temporomandibular joint disorders, since they only visualize major changes in shape of the osseous joint. In contrast, panoramic tomography is a standard imaging technique in this area. Its only disadvantage is minor summation effects that arise from the depth of the portrayed slice. In certain circumstances, small structural changes may not be reliably visualized. An image of the joint and neighboring structures that is largely free of superimpositions is achieved using various tomographic techniques and projections.

The use of CT allows osseous changes in the temporomandibular joint to be portrayed at a much higher sensitivity than with conventional radiological techniques. The advantages of CT are a high resolution and the 3D nature of the image. However, CT is not suitable for diagnosing the articular disc or portraying the ligament structures of the temporomandibular joint as it provides insufficient visualization of soft tissue.

By contrast, MRI is particularly adept at displaying non-osseous structures and, unlike CT, it does not use harmful x-rays. It is, therefore, at a very important tool in diagnosing temporomandibular joint pathologies. Like CT, MRI also has the advantage of generating 3D images.

The advent of CBVI has substantially expanded the options for diagnosing temporomandibular joint disorders, giving the treating dentist or oro-maxillofacial surgeon access to 3D information of the region without requiring a radiologist. Since CBVI is based on x-rays like CT, the display is comparable with that of a CT and studies have shown that there is no significant difference between the two techniques for temporomandibular joint diagnostics. However, MRI remains the method of choice for imaging soft tissue.

12.1.1 Developmental Disorders

The developmental disorders of the temporomandibular joint include condylar hyperplasia and condylar dysplasia. The latter has unclear etiology but it generally develops before 20 years of age from an autonomous activation of the growth zone in the condyle,¹ producing an isolated hyperdevelopment of the affected side of the mandible. Clinically, mandibular laterognathism can arise (lopsided face) with a unilateral open bite and a midline shift.² The enlargement of the condylar process can be discerned by radiography. An OPC is particularly suitable for diagnostics since it allows the two temporomandibular joints to be compared.



Fig 12-1 Male patient with condylar dysplasia and impaired growth of the right lower half of the face. The resulting laterognathism is particularly easy to identify in the 3D reconstruction.



Fig 12-2 A very rare doubling of the right mandibular condyle, probably post-traumatic.

Rarely occurring condylar dysplasias primarily arise in various manifestations of malformation syndromes (Figure 12-1). These include mandibulofacial dysostosis, cleidocranial dysostosis, Franceschetti syndrome, Goldenhar syndrome and Robin syndrome.² The condyle does not develop at all, or only develops rudimentarily. This dysplasia or hypoplasia of the growth zone leads to substantial disturbances in the growth of the entire lower face.

Another rare dysplasia, which is not associated with malformation syndromes, is the predominantly symmetrical doubling of the mandibular condyle (Figure 12-2).

12.1.2 Primary Acquired Diseases

Primary acquired diseases affecting the temporomandibular joint include inflammatory disorders (traumatic and infectious arthritis, chronic polyarthritis, psoriatic arthritis, ankylosing spondylarthritis), synovial chondromatosis and rare tumors of the temporomandibular joint.

Inflammations of the temporomandibular joint can cause displacement of the mandibular condyle in a ventrocaudal direction owing to joint effusion. This results in an open bite on the diseased side and a shift of the mandible to the opposite side (Bonnet's position), which under certain circumstances can be identified by a technique such as CBVI.³ In the late stage of arthritis, especially in chronic polyarthritis, ankylosis of the joint may occur (Figure 12-3).^{4,5}

Synovial chondromatosis is a metaplasia of the synovial fluid of an unclear etiology; it is very rare in the temporomandibular joint. Synovial cartilage foci arise that are released into the articular cavity and exist as free joint bodies in the articular space.^{2,6} Unfortunately, CBVI has not yet been used to examine synovial chondromatosis.

Benign and malignant tumors of the temporomandibular joint are also rare.⁷ The most common benign tumor is the osteochondroma. Tumors that occur much less frequently in the temporomandibular joints are osteomas, chondromas, giant cell granulomas, myxomas, hemangiomas, ameloblastomas and eosinophilic granulomas.¹

Malignant tumors of the temporomandibular joint are generally osteogenic metastases of breast, kidney, lung and prostate carcinoma. Much rarer are primary malignant diseases of the temporomandibular joints, such as chondrosarcoma and fibrosarcoma, synovial sarcoma and osteosarcoma.^{8,9} Unfortunately, here too there are no CBVI data.



Fig 12-3 Patient with ankylosis in both temporomandibular joints.



Fig 12-4 A male patient with right-side osteoarthritis that has caused major degeneration of the articular process.

12.1.3 Secondary Acquired Diseases

Secondary diseases of the temporomandibular joint arise as a result of malfunctions in the stomatognathic system. While there are many causes, malocclusion is the primary factor in the generation of these secondary diseases, which include temporomandibular osteoarthritis, disc perforations and luxations, inflammatory disturbances and luxations of the condyle.³

Osteoarthritis

Temporomandibular osteoarthritis (arthrosis deformans) is a non-inflammatory degenerative change resulting from years of functional disturbances, trauma or overloading of the temporomandibular joint (Figure 12-4). Type I osteoarthritis primarily affects the elderly and initially arises on one side, always followed by occurrence on the other side at a later time. It clinically manifests as a combination of crepitation and function-related pain. A discless joint usually results. Type II osteoarthritis arises from trauma or other temporomandibular joint problems lasting a number of years, and it is generally restricted to one side. The patient experiences progressive pain and functional impairment.²

Changes in and destruction of the cartilage initiate degenerative processes in the subchondral bone, with osteoclastic activity. Typical radiological changes are the reduction of the articular space, eroded surfaces, subchondral sclerosing of the spongiosa, osteophytes and, more rarely, subchondral cysts and free intra-articular bodies. In the last stage of arthrosis deformans, osteolysis arises in the subchondral region of the capitulum accompanied by the secondary destruction of the joint surfaces. Furthermore, erosion and the formation of marginal spikes occur at the condylar surface, with discrete subchondral decalcification.¹

Ankylosis

In ankylosis, portions of the joint become fixed by connective tissue (fibrotic) or by osseous adhesion (Figure 12-3). Osseous ankylosis is very rare and generally results from joint trauma or inflammatory changes in the joint (chronic arthritis) or its surroundings (otitis media, mastoiditis). Fibrous

ankylosis occurs much more frequently. Generally the disc and articular fossa are immobilized by connective tissue. Possible causes are hematomas after injuries or surgery, as well as long-term synovitis.² Ankylosis is particularly common after luxation fractures of the temporomandibular joint that occur before bone growth has concluded. Clinically, both forms are marked by various degrees of trismus.

12.2 References

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13 Craniofacial Malformations and Syndromes

Joachim E. Zöller and Mitra Saffar

This chapter addresses the malformations and most important systemic syndromes that manifest symptoms in the region of the visceral cranium.

13.1 Cleft Lip and Palate

Clefts of the lip, alveolar process, hard palate and soft palate belong to the category of craniofacial dysplasias, even though they only affect the visceral cranium and are, therefore, strictly speaking "facial" deformations.^{1,2} They are among the most common congenital malformations and arise from developmental disorders in the area of the embryonic head and the first two visceral arches including the neighboring clefts. Cleft lip and palate manifests in numerous forms and degrees of seriousness.³ The extraoral and intraoral appearance is decisively influenced by the morphological malformation of the nasomaxillary complex. Esthetic and functional problems result. Usually, the facial esthetics of the affected patients are substantially impaired. This generally results in psychological problems both inside and outside of family. In addition to esthetic difficulties, patients predominantly experience functional impairment of occlusion and articulation, as well as disturbances in speech, hearing and respiration.

The prevalence of this disorder is presently held to be 1 in 750. Today, the pathogenesis is assumed to be multicausal. In addition to a genetic component and malnutrition (especially insufficient folic acid intake), a primary cause is actinic radiation trauma.

The critical time for the development of cleft lip and palate is during the development of the primary palate in the fifth embryonic week and during the formation of the secondary palate between the seventh and ninth weeks.

Congenital clefts vary widely between individuals and manifest as lateral clefts in the upper lip, the alveolar process and the soft palate; they occur either unilaterally or bilaterally and can form complete or incomplete clefts. Cleft combinations are more common than isolated clefts. The etiology and morphology gives rise to two major groups: those exhibiting a cleft in the lip and jaw with or without a palatal cleft, and those with isolated cleft palates after the undisturbed development of lips and jaw.

13.1.1 Special Symptoms in the Region of the Visceral Cranium

Depending on the type of cleft, the primary clinical symptoms include unilateral or bilateral hypoplastic developmental variants in the region of the midface and alveolar process, with distortions of the nasal wings and lowering of the tip of the nose.⁴ Only hypoplasia, quite apparent in most clefts, is clinically manifested by an often substantially flattened, retracted profile of the subnasal region with a positive lip profile.

Patients with clefts of the lip, jaw and palate exhibit numerous dentoalveolar and dental developmental disorders in addition to the congenital defect. A maxillary growth deficit arises from scarification and the absence of timely therapy. This is clinically manifested as midfacial hypoplasia with pseudoprognathism. In addition, individuals with cleft lip and palate manifest typical displacements of individual teeth near the cleft, as well as characteristic displacements of incisor and posterior tooth groups, which again are substantially influenced by the anatomical arrangement of the cleft jaw segments (Figure 13-1).^{5,6} In addition, atypical tooth shapes and sizes occur, which are not necessarily limited to the cleft region. The most frequent local dentition disorders include anomalies in the number of teeth and associated micro-symptoms, especially the displacement of the cuspids near the cleft, and mineralization disturbances of the incisors.

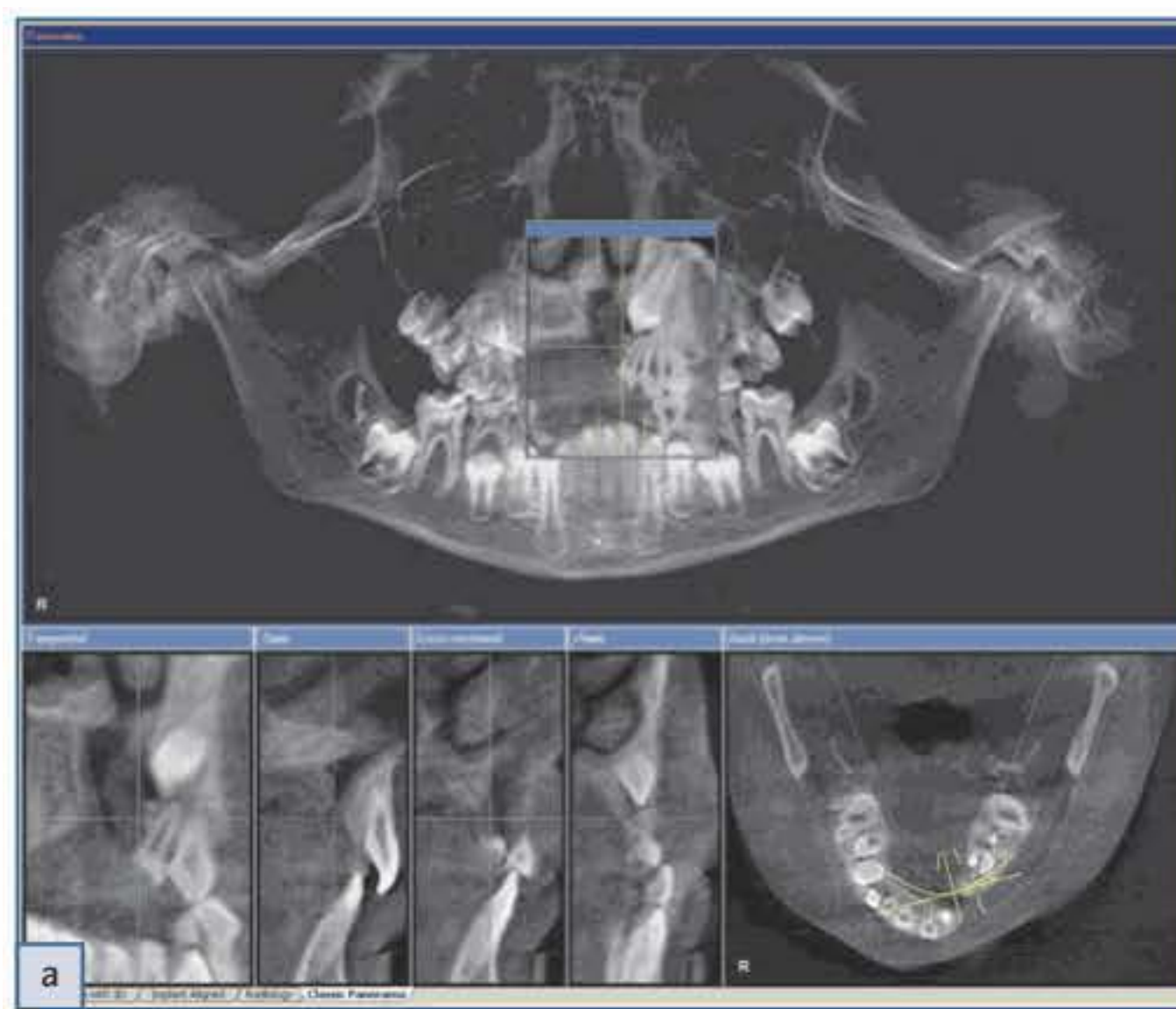


Fig 13-1 Left cleft lip and palate in a child. (a) The precise extent of the cleft can be determined in the reconstructed panoramic image. The position of the segments is also revealed, and the left posterior tooth segment is shifted in a palatal direction. Tooth 23 is displaced far cranially. The positional relationship to the hard tissue cleft can be clearly evaluated. (b) No manifestation of developmental disturbance is seen in the right segment, but a visible growth deficit occurs in the left segment. This is particularly clear in the 3D perspective. Likewise, the base of the septum is asymmetrical, corresponding to the cleft formation.

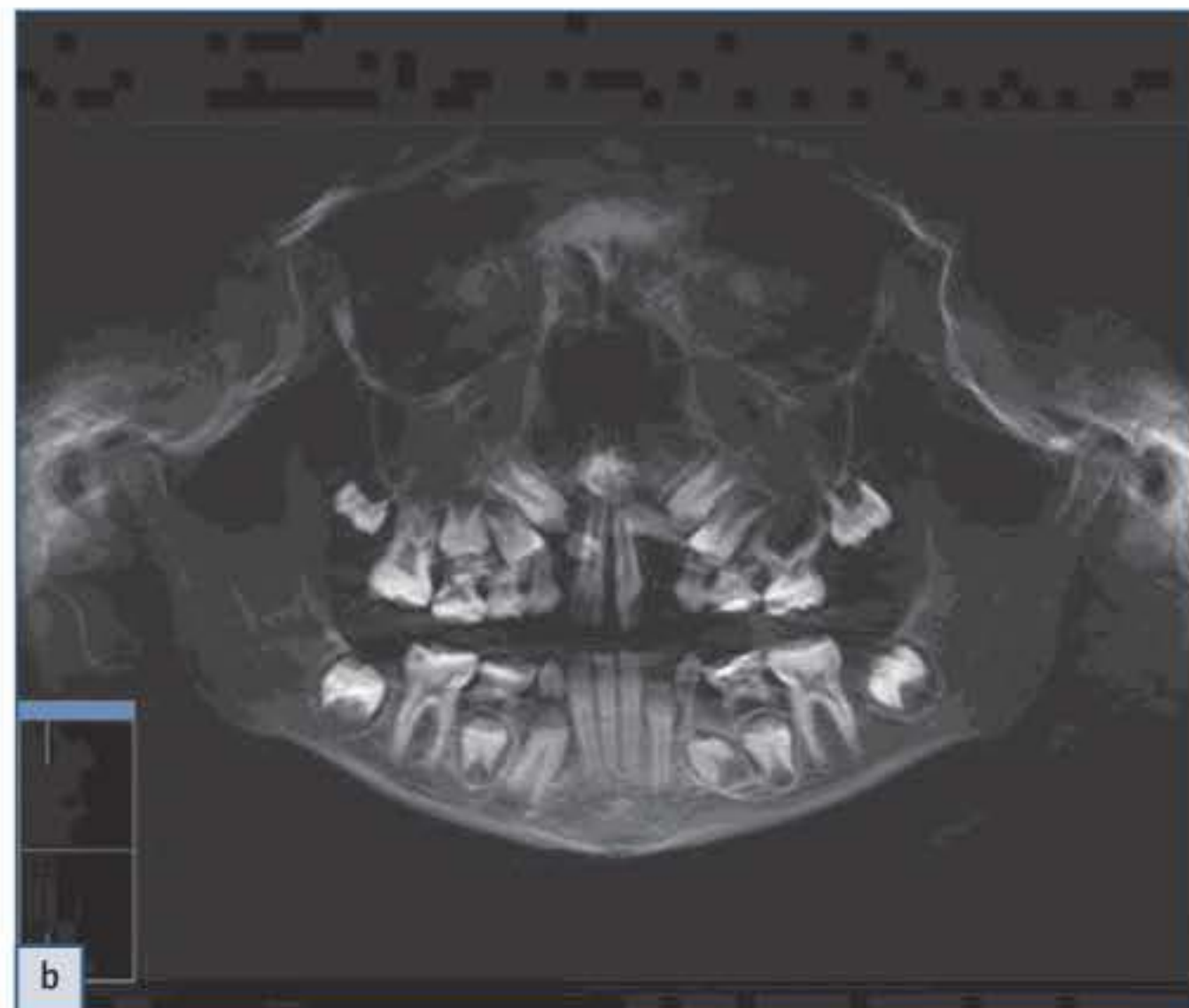


Fig 13-2 Cleft lip and palate. (a) Good visualization of the premaxilla, particularly in the axial slice. The lateral segments are compressed, and there is also an anterior growth disturbance. An incipient mandibular hypertrophy can already be visualized. (b) The positions of the ectopic canines in a bilateral cleft is easy to determine in the panoramic reconstruction. The edges of the alveolar process near the cleft are drawn in a cranial direction.

In general, the area surrounding the cleft is characterized by a more-or-less pronounced hypoplasia of the osseous nasomaxillary complex. The conventional findings for a unilateral cleft include asymmetrical deformations of the osseous nasal lumen with a pronounced septal deviation toward the side of the cleft. Unilateral and bilateral clefts of the alveolar process are distinguished by a vertical reduction in the height of the alveolar process in the region of clefts. The edges of the alveolar process close to the cleft are generally drawn toward the cranium (Figure 13-2). In addition, differential diagnosis can distinguish between various shapes and degrees of seriousness of the maxillary developmental deficit and, in certain circumstances, of mandibular overdevelopment.

13.1.2 Special Diagnostics

Basic radiological diagnostics have previously been carried out in steps involving OPCs, dental films, transverse tomographs and culminating in CT. However, CBVI allows anatomically precise information in 3D to be obtained regarding the type of cleft, the extent of the defect and the residual defects after secondary osteoplasty.⁷ It also makes treatment planning more effective as the anatomical relations of the cleft and its morphology are clearly apparent and easier to evaluate than clinical findings or 2D images alone (Figure 13-3).



Fig 13-3 Bilateral cleft lip and palate. (a) Panoramic reconstruction demonstrates the necessity of a secondary osteoplasty. An osseous bridge exists on the left side in the region of the nasal floor. Likewise, the positional relationship of the impacted teeth to the cleft can be distinguished. (b) Growth disturbances of the lateral segments are revealed in the axial and transverse slices. The cleft area is also asymmetrical, resulting in a septal deviation.



Fig 13-4 Highly pronounced midfacial hypoplasia in a girl with Apert syndrome. The girl underwent partial dental compensation, yielding edge-to-edge bite. There was no hypertelorism. Since the orbital apex was very small, a protrusion of the eyeball can be seen in the region of the soft tissue.

13.2 Syndromes

A syndrome is a clinical picture that always manifests roughly the same signs of disease (i.e. with a largely identical “pattern of symptoms”) where the etiology is unknown, ambiguous, polyetiological and pathogenetic with multiple causes, or where the etiology is only partially known.^{8–10}

13.2.1 Apert Syndrome (Acrocephalosyndactyly Syndrome)

Like Pfeiffer syndrome and Saethre–Chotzen syndrome, Apert syndrome belongs to the acrosyndactylies.¹¹ It is an autosomal dominant congenital disorder, but the predominant number of cases represent new mutations. The essential malformations include craniosynostosis, facial dysmorphism and syndactylies. Oxycephalic growth generally occurs owing to the premature closure of primarily the coronal sutures. The facial dysmorphisms are associated with a wide, hypoplastic face, exophthalmus, downward-slanting palpebral fissures, strabismus, hypertelorism and gothic palate (Figure 13-4), abnormal tooth positions and elevated palate, combined with cleft formation. Typical manifestations are low set ears and an often small, upturned, beak-shaped nose, also known as parrot nose, which is sometimes incorrectly ascribed to Crouzon syndrome. Membranous and osseous (generally bilateral) symmetrical syndactylies of the hands and feet are characteristic, frequently involving four fingers or toes. This results in so-called “spoon hands”. More rarely, other concomitant diseases occur such as anomalies in the trachea and lungs, heart defects, polycystic kidneys and uterine malformations.

13.2.2 Cleidocranial Dysostosis (Scheutauer–Marie–Sainton Syndrome)

Distinguishing features of cleidocranial dysostosis are a wide cerebral cranium with frontal or parietal eminences associated with visible depressions above the glabella. The visceral cranium is relatively small with a wide and low nasal root as well as exophthalmus. Less frequently, hypoplasia or dysplasia of the collarbones occurs, with hypermobility of the shoulders. The dentition is delayed, and supernumerary teeth as well as hypoplasia of the maxilla are found (Figures 13-5 and 13-6).

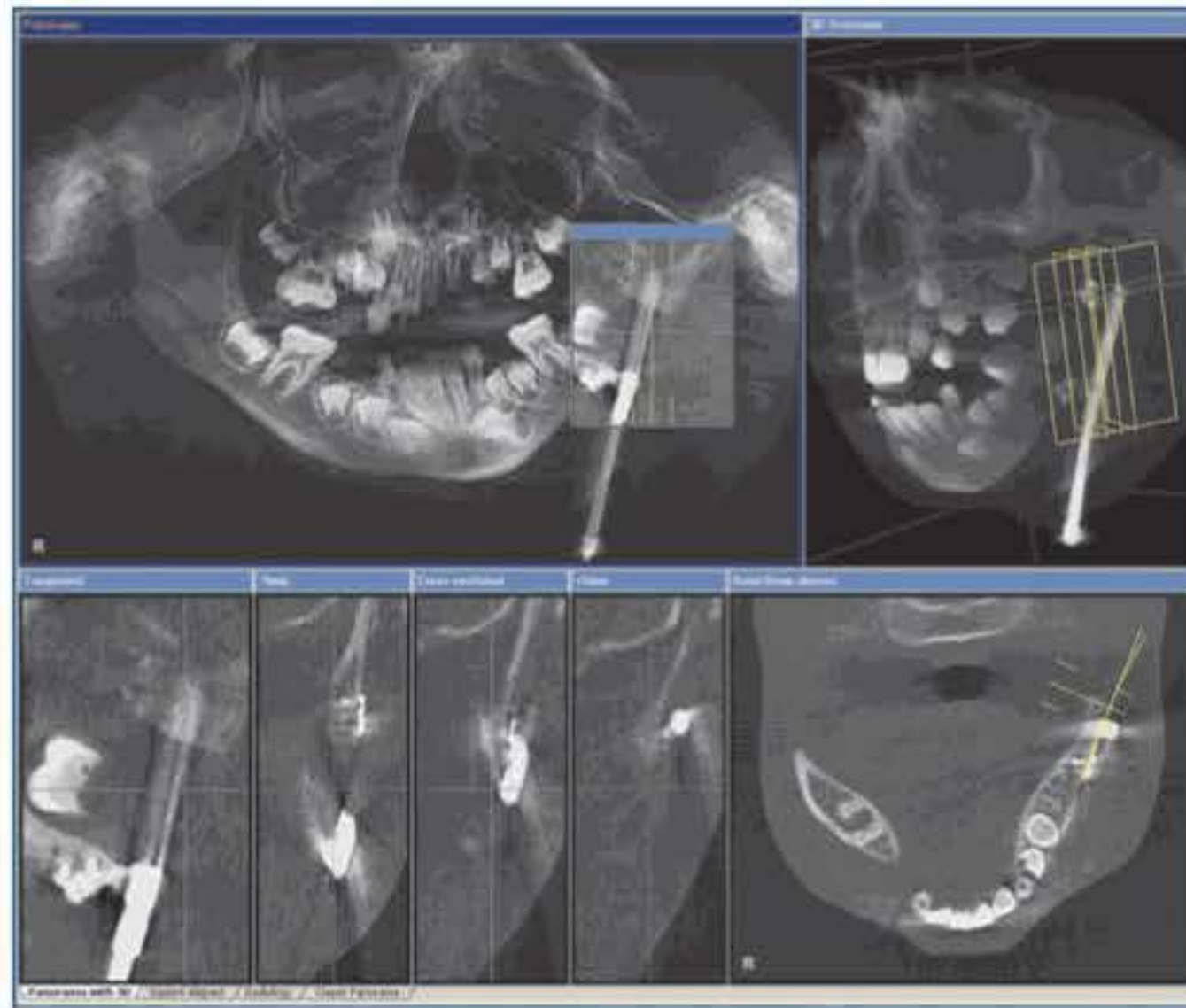


Fig 13-5 Child with multiple tooth impactions. (a) In the mandible, the premolars on both sides have orthodontic brackets adhered to them. The midface is slightly hypoplastic. (b) Vertically stacked slices permit a precise evaluation of the position and extent of each tooth impaction. The maxillary sinuses are only slightly developed. There is a marked septal deviation to the left.



Fig 13-6 Child with multiple tooth impactions. (a) Panoramic reconstruction revealed the impactions plus the precise location of the impacted cusps with adhered brackets. (b) Midfacial growth is not impaired by the tooth impactions. The 3D position of the impacted premolars can be clearly evaluated.

Fig 13-7 Boy with left hemihypoplasia of the mandible; an osteotomy was performed, followed by a distraction of the ramus of the mandible on the left side. The images reveal substantial achievement of symmetry. The callus is not yet mineralized and is, therefore, indistinctly visualized.



13.2.3 Goldenhar Syndrome (Oculoauriculovertebral Dysplasia)

Goldenhar syndrome is a characteristically combined malformation in the oculo-auricular region (Lat. *dysplasia oculo-auricularis*) caused by developmental and differentiation disturbances in the area of the dental arch and the first pharyngeal cleft (first and second visceral arches), which generally arises via new mutation. In 1952, Maurice Goldenhar examined this malformation for his medical thesis at the Geneva University Ophthalmology Clinic and summarized the symptoms.

The syndrome is a facial asymmetry with hemihypoplasia of the mandible and the face. It is partially associated with cleft lip and palate and/or oral clefts as well as microgenia/retrogenia (and possibly also with supernumerary or missing teeth). Generally, the findings are strictly unilateral. Notable is hypoplasia of an auricle with preauricular appendages and similar malformations (e.g. preauricular fistula) at the line between the angle of the mouth and the ear. Epibulbar dermoids are observed, generally located laterally on the lower lid, whereas lipodermoids and colobomas are usually found on the upper lid.¹²

Radiologically, the more-or-less pronounced asymmetry of the visceral cranium is distinguished by unilateral hypoplasia of the zygomatic arch region and the mandible (Figure 13-7).

13.3 Mandibular Hypoplasia in Osteomyelitis

In addition to congenital malformations of the osseous structures, early childhood trauma and inflammatory processes such as osteomyelitis arising from otitis media cause malformations and developmental disturbances in the area of the temporomandibular joint and the mandibular ramus. Attempts are still frequently made to compensate dentally for malformations in the facial area that were not recognized at an early stage. However, these attempts can cause developmental disorders that only become apparent in a growth spurt.¹³



Fig 13-8 Pronounced mandibular deformity in a boy with bilateral early childhood osteomyelitis. The mandibular collums are hypoplastic. A wire suture is discernible on the left in the region of the socket. (b) Vertical planes revealing the wire sutures in the sockets on both sides that retain interposing Silastic blocks. Despite the correction of the bilateral joint osteoarthritis, the articular spaces are difficult to discern. Clinically, there is a marked restriction of movement of the mandible.

Ankylosis of the temporomandibular joint is the adhesion of the temporomandibular joint to the base of the skull. It can occur following condylar process fracture or inflammatory processes and manifests as a limited ability to open the mouth. If it arises in early childhood, the growth of the mandible can be impaired, which leads to pronounced mandibular retrognathism (Figure 13-8).

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Treatment Planning

14 Implant Planning

Jörg Neugebauer, Lutz Ritter and Joachim E. Zöller

Inserting dental implants to anchor tooth reconstruction is part of today's established spectrum of therapies offered by dentists to restore chewing and speech function. Implants are used in all indications, to introduce an individual crown or bridge or to anchor a removable restoration. Ideally, implants are inserted into the non-atrophied jaw that previously anchored the tooth. However, tooth loss frequently results in a reduced volume of the alveolar process; consequently, anatomical conditions require a precise spatial orientation for implant positioning to ensure that future prosthetic accommodations meet the patient's esthetic and functional needs.

For classical implant planning, bone availability can be sufficiently determined via 2D tomography or dental films. The panoramic tomograph facilitates the localization of the anatomical structures that need to be protected, such as the inferior alveolar nerve, the floor of the maxillary sinuses and of the nose, as well as the mandibular border and the remaining teeth. Depending on the system, these tomographs enlarge the anatomical structures by 25 to 30%. However, enlargement within the image is not uniform. The enlargement factor fluctuates depending on the design of the equipment and the positioning of the patient during imaging. Therefore, such images should be calibrated using metallic reference balls so that the actual size of the anatomical structures can be calculated. However, panoramic tomography only permits a limited evaluation of the existing structures, especially if a spatial representation of the vertical and horizontal bone bed is required. Erroneous positioning of implants may result, involving damage to important anatomical structures. Taking transverse tomographs may improve the situation. Below, the use of 3D diagnostics and therapy planning is discussed.

14.1 Diagnostics and Establishment of Indication

To determine the precise therapeutic scope of a prosthetic implant therapy to restore chewing function, it is important to evaluate existing bone availability both quantitatively and qualitatively. This will indicate whether augmentation is necessary and identify the prosthetic restoration options. Through the visualization of the available bone and the analysis of the extent of required prosthetic treatment, the treatment plan can be worked out with the patient. This is much easier when using 3D diagnostics than using illustration with classical images.

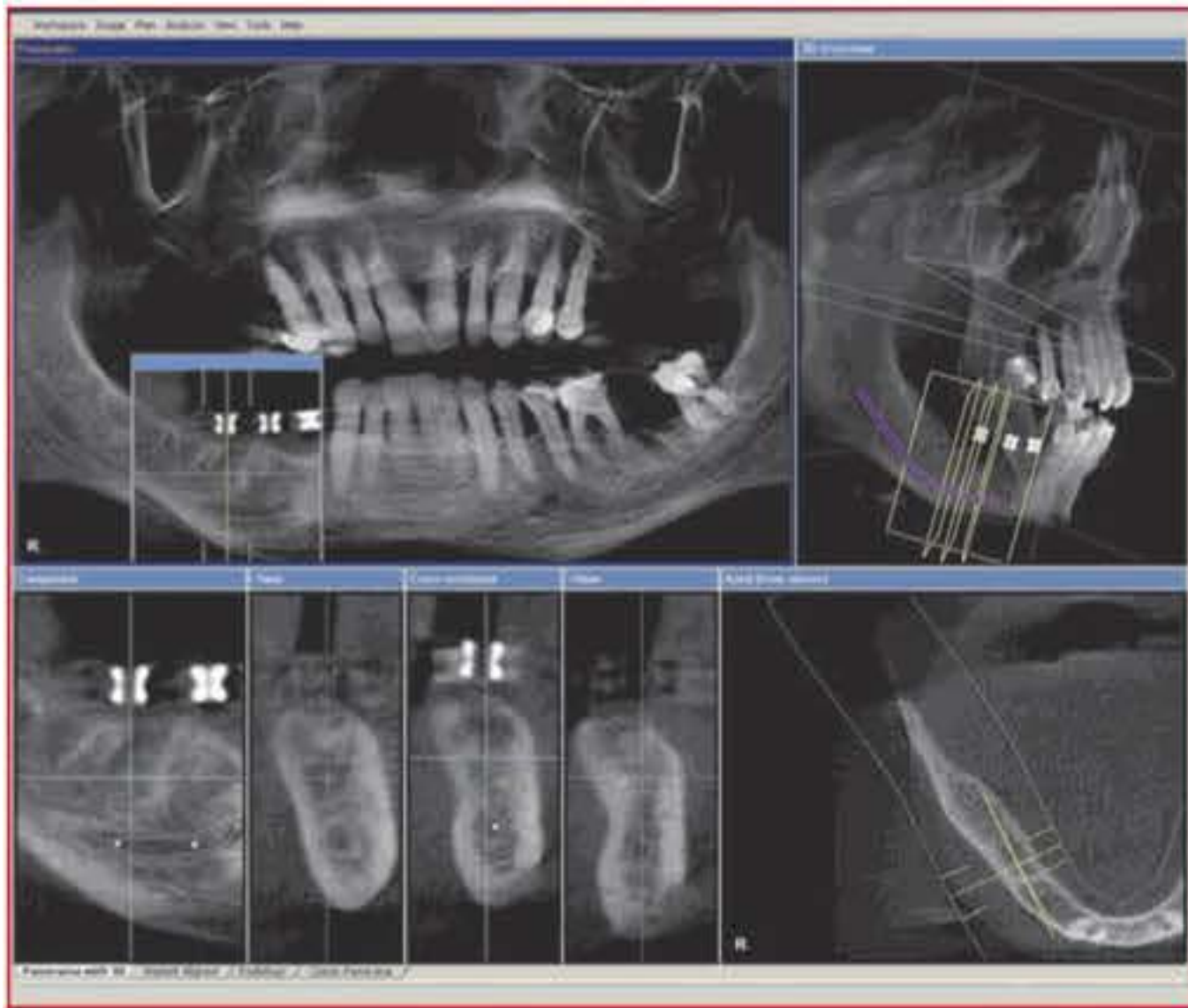


Fig 14-1 Planning of three implants to replace teeth 44 through 46. Display of the drill sleeves positioned according to technical considerations, with deviations in angulation and still adequate bone availability.

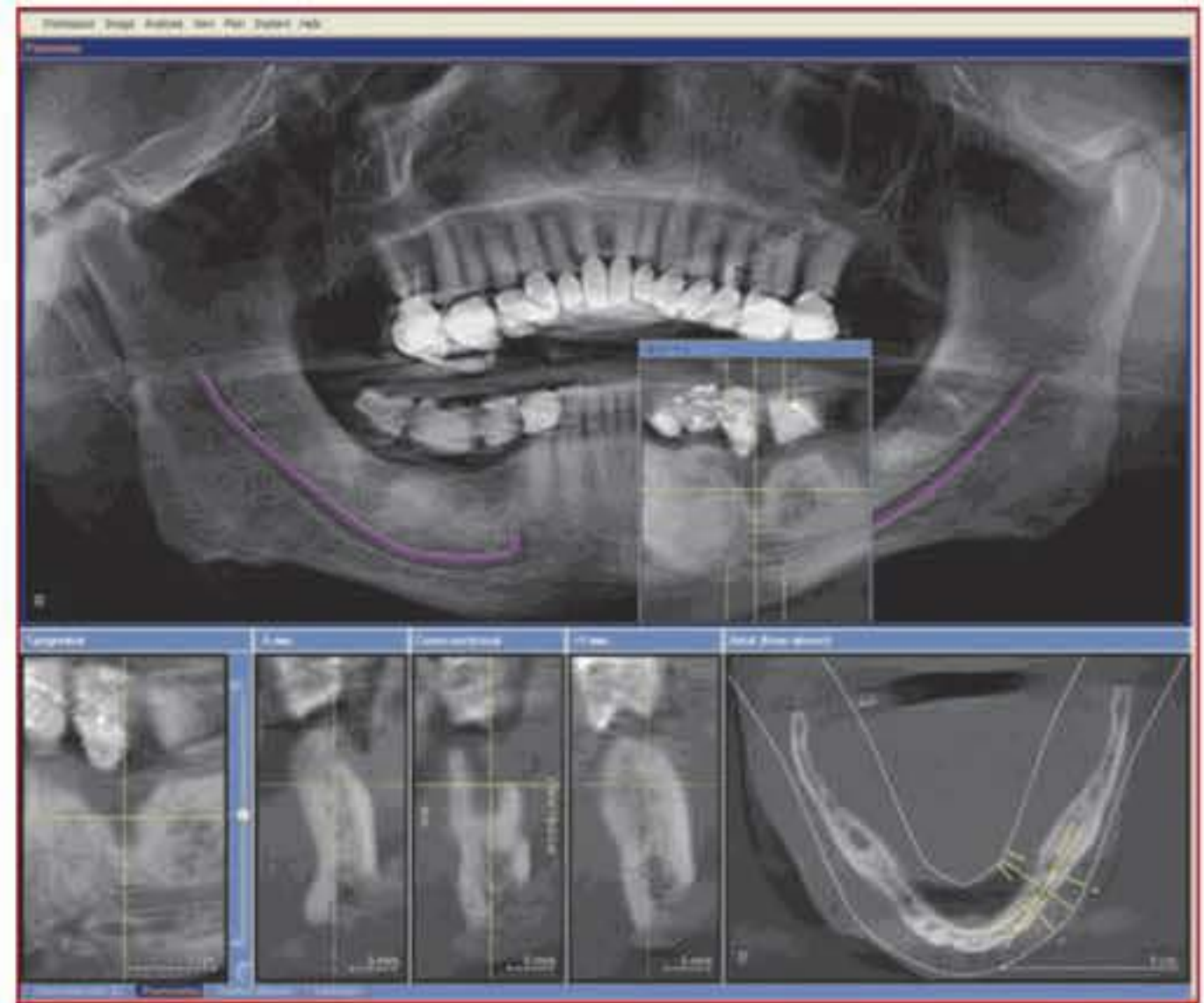


Fig 14-2 Prosthetic treatment proposal prepared in barium sulfate vacuum-formed stent for the purposes of orientation in the determination of implant positions.

14.1.1 Quantitative Evaluation of Bone Availability

Three-dimensional diagnostics provides a measurement feature for metric analysis. Since the imaging of the slices has already been metrically calibrated, it is not necessary to use a reference ball for calibration, as required in the panoramic tomograph. Bone availability can be determined in the horizontal and vertical dimensions using the measurement function. However, in addition to a purely quantitative analysis, it is also important to be oriented as to the position of the prosthetic device when planning a procedure. This can be done using a classic drill template by depicting the drill sleeves attached by the dental technician or by using an x-ray template (Figure 14-1). The latter results from the prosthetic proposal of the dental technician (backward planning), implemented in a radiological template containing barium sulfate, which is radiopaque in the image. Even when sufficient bone is available for implant insertion, it may not be possible to utilize it if the positioning could lead to difficulties with the prosthetic axis. In using a prosthetic proposal, the best implant position can be selected without requiring further augmentative procedures (Figure 14-2).

14.1.2 Qualitative Evaluation of Bone Availability

A surgeon who is aware of the bone quality can plan the procedure, particularly for drilling pilot holes. The often highly cortical structure in the posterior mandibular area abuts the soft spongoid medullary cavity area. Depending on the cutting behavior of the drill, a large amount of force may be needed to prepare the cortical bone. After preparing the implant cavity in the cortical bone, it is very easy to make the preparation too deep in the subsequent soft sections of the spongiosa, resulting in damage to anatomical structures (Figure 14-3).



Fig 14-3 Evaluation of bone quality in the area of the right mental foramen with pronounced cortical bone, dense spongiosa in the interforaminal area, and wide-meshed spongiosa in the posterior area.



Fig 14-4 Planning of implant insertion in region 44 with almost complete root resorption of tooth 84 and significant retraction of the alveolar process and lack of spongiosa. Because of the broad crestal alveolar ridge, bone chip augmentation of the apical perforation area is planned during implant insertion.



Fig 14-5 Planning of implant insertion in a patient with multiple maxillary agenesis. The bone structure in region 25 indicates a pronounced thin cortical layer vestibularly, with a slightly mineralized finely meshed spongiosa.

If the bone in the mandible is very cortical, preoperative diagnostics also permits the planned use of intermediate drills to ensure very careful preparation. The cortical structures of the mandible particularly can yield bone chips for use in regional augmentation where bone availability is reduced (Figure 14-4).

If osteotomes are used for implant bed preparation, in particular in the maxilla,¹ CBVI provides precise information on the trabecular structure of the bone. The optional use of a bone condenser can be precisely planned (Figure 14-5). If cortical structures predominate, one can resort to classical drill preparation early on, and complications associated with cortical damage and consequent bone resorption can be reduced.²

14.2 Indication-specific Implant Planning

In prosthetic implant restoration of several missing teeth, it is advisable to prepare a wax-up to simulate the prosthetically desired result. A wax-up provides a point of reference for the best prosthetic position of the implant suprastructures. For further processing, the wax-up is mated with a silicone wall, so that it is possible to stay oriented as to the prosthetically planned result on the model after removal of the wax-up (backward planning).

In restorations where esthetics are less relevant, such as in the posterior tooth area of the mandible or in bar restorations, direct use of the wax-up to produce a drill template may be adequate.

The implant position is determined on the model using the model parameters and taking into account soft tissue thickness. By drilling into the cast, a pin can be placed and the titanium sleeve aligned to it. The silicone wall is re-applied, and the sleeves are fixed with acrylic resin according to the prosthetic set-up. Alternatively, the sleeves can also be fixed using a tray that has been fabricated with the wax-up. In these drilling templates, deviations in the implant axis with respect to the existing bone availability can occur following 3D diagnostics, which then must be either corrected by the dental technician or adjusted during implantation by the dentist.

In more complex cases that require precise positioning both in the orovestibular and in the mesiodistal directions, particularly in the anterior maxilla or for a planned fixed prosthetic, it is advisable to implement the prosthetic set-up using a radiological template. In this process, the teeth to be replaced are produced in barium sulfate-doped acrylic resin using a vacuum form. The teeth must make flush mucosal contact so that the dimension of the soft tissue can be determined accordingly. In addition, the crowns must be separated so that simple and logical orientation of the tooth position is possible. Alternatively, specially prefabricated teeth can be set up or the central axis of the intended design can be simulated by the dental technician by incorporating a gutta-percha pin. Depending on the planning system used, the system-specific reference must be fixed to the radiological template, ensuring a precise transfer to the planning software.

14.2.1 Implantation into the Anterior Mandible

Implant insertion in an edentulous mandible is still the most frequent indication, especially since at least four implants are usually inserted in each patient. Bone availability varies depending on the level of atrophy. If the alveolar process is still intact, the bone is often significantly reduced in the orovestibular direction. In a so-called "knife-edge" alveolar ridge, implant insertion is impossible without prior onlay osteoplasty or significant shortening (Figure 14-6). As its height drops, the ridge becomes appreciably wider. However, surgeons must avoid placing the implants too far lingually when planning the implant. In addition to the estimation of bone quality, CBVI also facilitates the evaluation of the opposite cortical bone (Figures 14-7 and 14-8). Through 3D analysis, the extent of the fovea submentalis and any recesses created by the lingual artery can be evaluated. A basal or lingual perforation must be avoided, since arterial damage can result in life-threatening bleeding, with submental hematomas (Figure 14-9).



Fig 14-6 Edentulous mandible with pronounced atrophy in region 45 in the area of the mental foramen with the need for augmentation, since shortening the alveolar ridge would result in an insufficient vertical dimension for implant insertion.

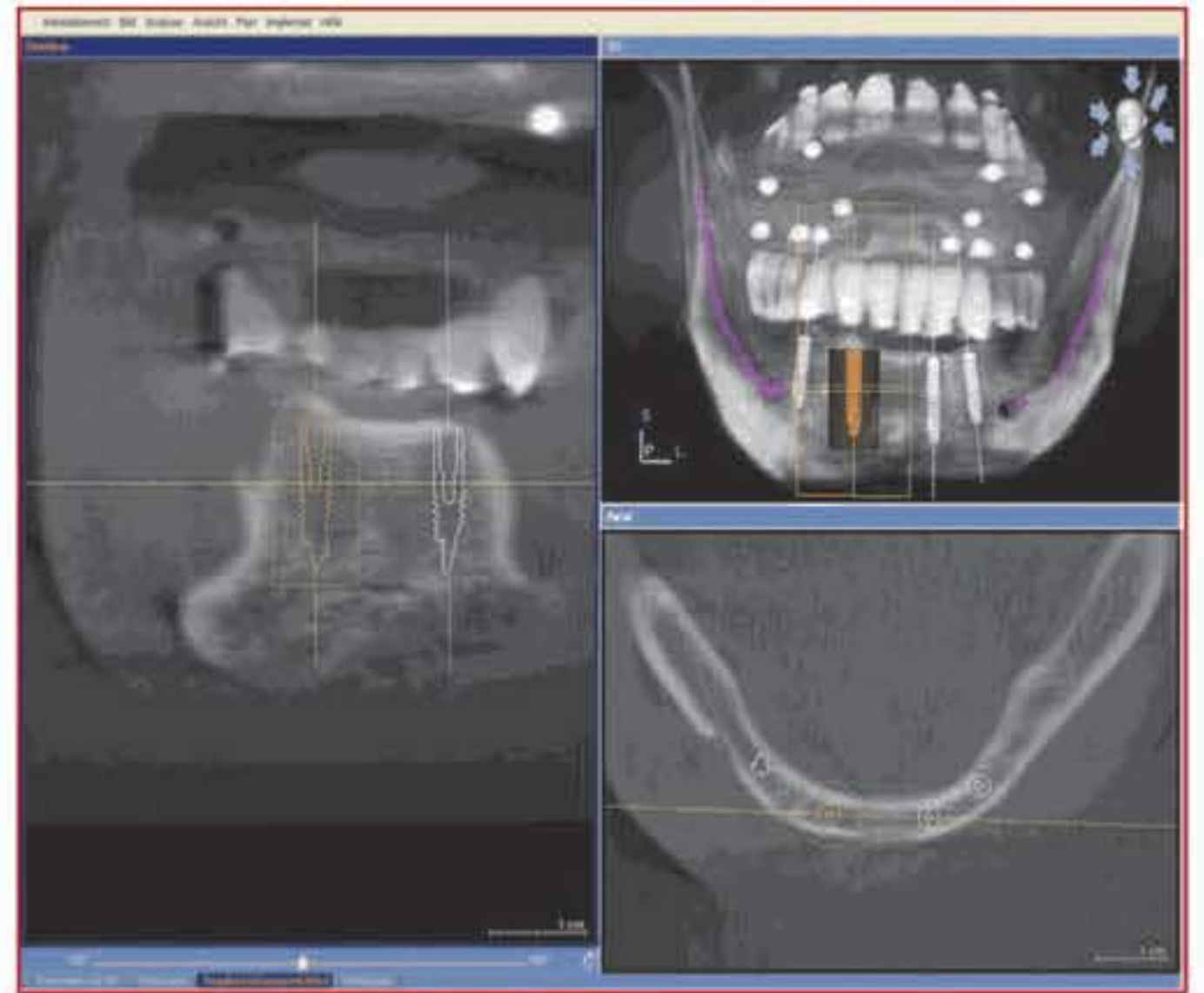


Fig 14-7 Plan for the insertion of four intraforaminal implants in the mandible, protecting the lingual and vestibular cortical bone at 1.5 mm of osseous lamina. Superimposed around implant 42 is a safety distance of 2 mm horizontally and 1 mm vertically.



Fig 14-8 Implant planned in region 42 with the implant position being shifted slightly lingually compared with the prosthetic set-up. The vertical implant position was chosen at a slightly subcrestal position to ensure the width of the vestibular and lingual bone supply.



Fig 14-9 Implant planned in the anterior mandible with a prosthetic proposal located far vestibularly relative to the local bone, with display of the fovea sub-mentalis.



Fig 14-10 *Diagnostics in a case of bilateral free-end situation with display of the profile of the mylohyoid line to determine possible implant insertion.*

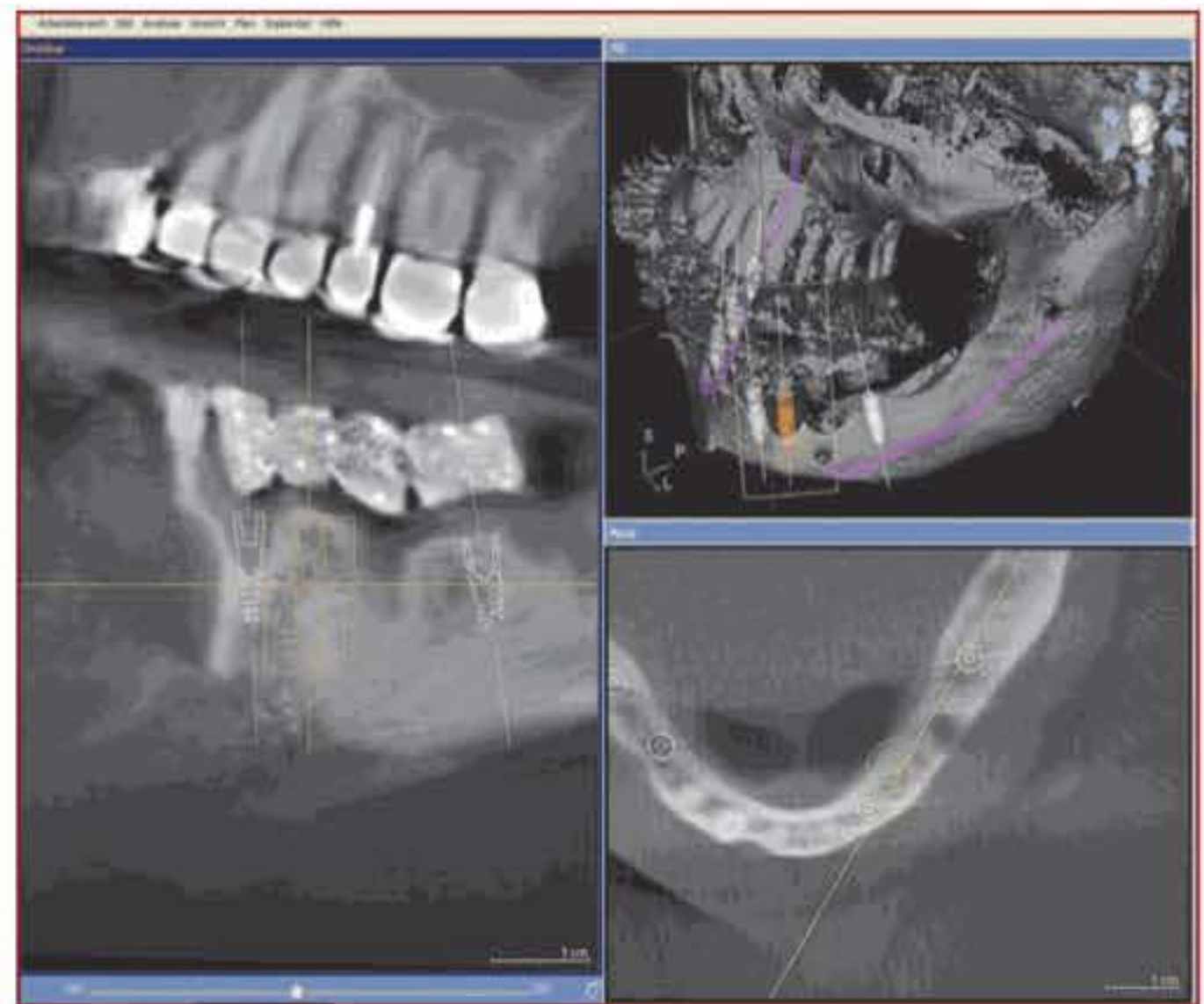


Fig 14-11 *Implant plan in accordance with the prosthetic requirements of 33 to 36, with optimal use of the available bone.*



Fig 14-12 *Implant plan with consideration of the antagonistic dentition from 44 to 47.*

14.2.2 Implantation into the Posterior Mandible

Implantation in the posterior mandibular area is generally done unilaterally to obviate the need for a removable tooth replacement, or bilaterally after a longer period of edentulism and loss of multiple support teeth. For implantation in the direct vicinity of the inferior alveolar nerve, the bone supply between the nerve channel and the crestal profile of the alveolar ridge must be exactly measured. CBVI permits a precise representation of the nerve channel profile, especially in the region of the mental foramen. This significantly reduces the risk of nerve damage during implant insertion in a nerve channel that runs anteriorly from the mental foramen.

Similarly to the fovea submentalis in the diagnosis of the anterior mandible, the profile of the mylohyoid line can be precisely analyzed using CBVI (Figures 14-10 to 14-15).

Fig 14-13 Implant planning in region 45 with reduced bone availability using a D3.4 L13 implant anchored in the lingual and vestibular cortical bone while protecting the lingual fovea.

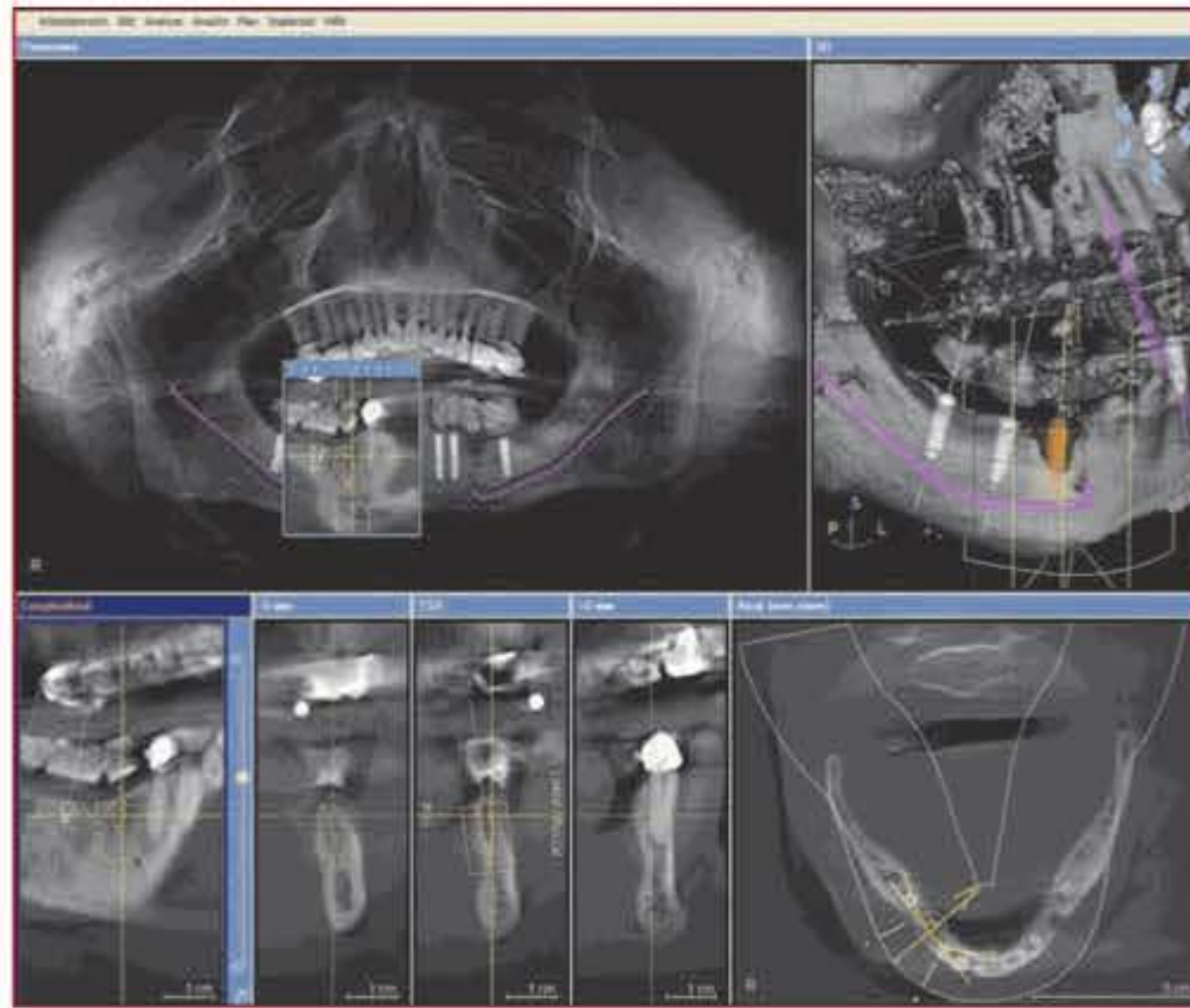


Fig 14-14 Planning of implant insertion in region 33 with a crestal bone defect that has to be augmented with bone chips.

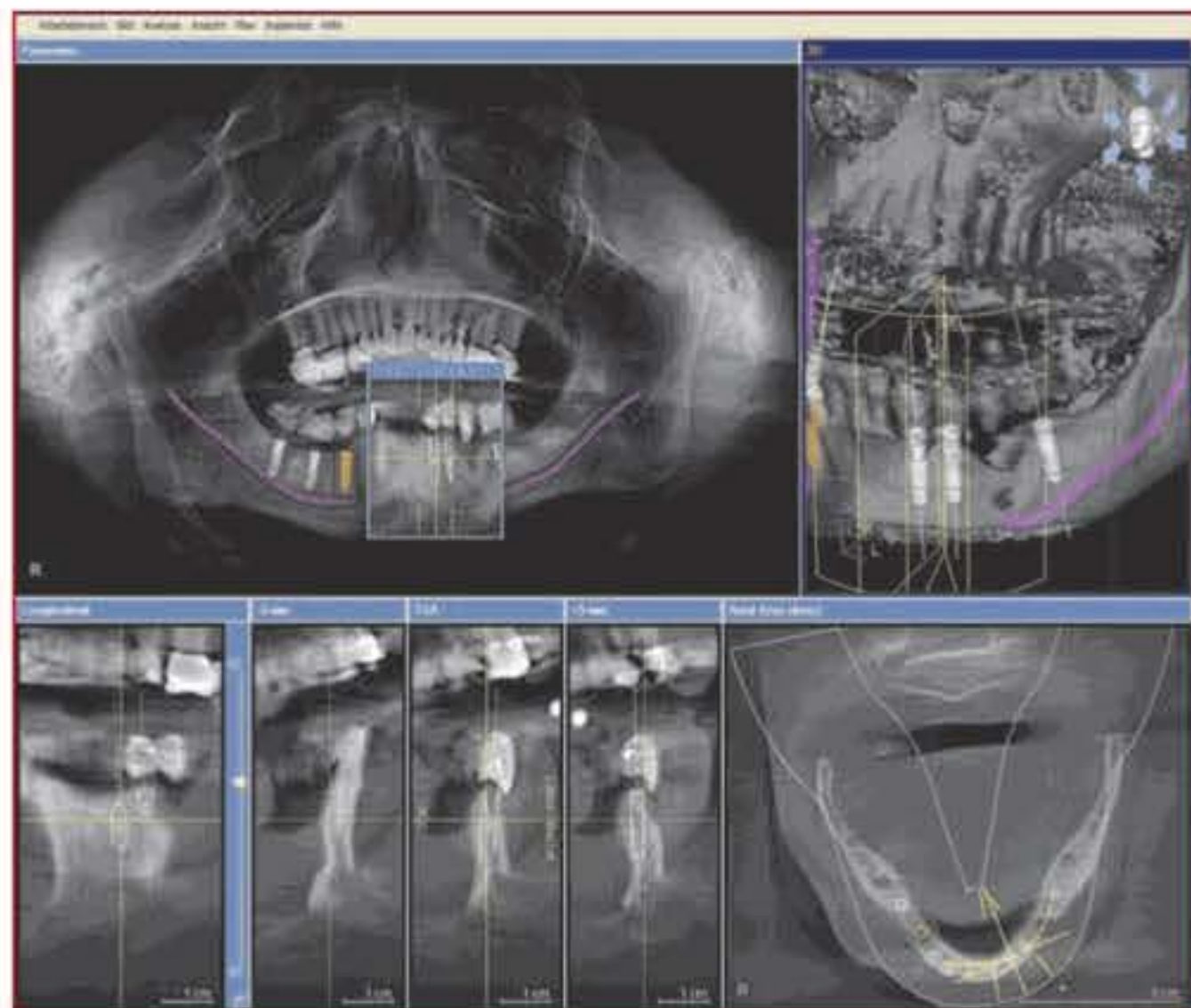


Fig 14-15 Postoperative control scan after the insertion of six implants. The placement of the bone chips is not visible in the CBVI.

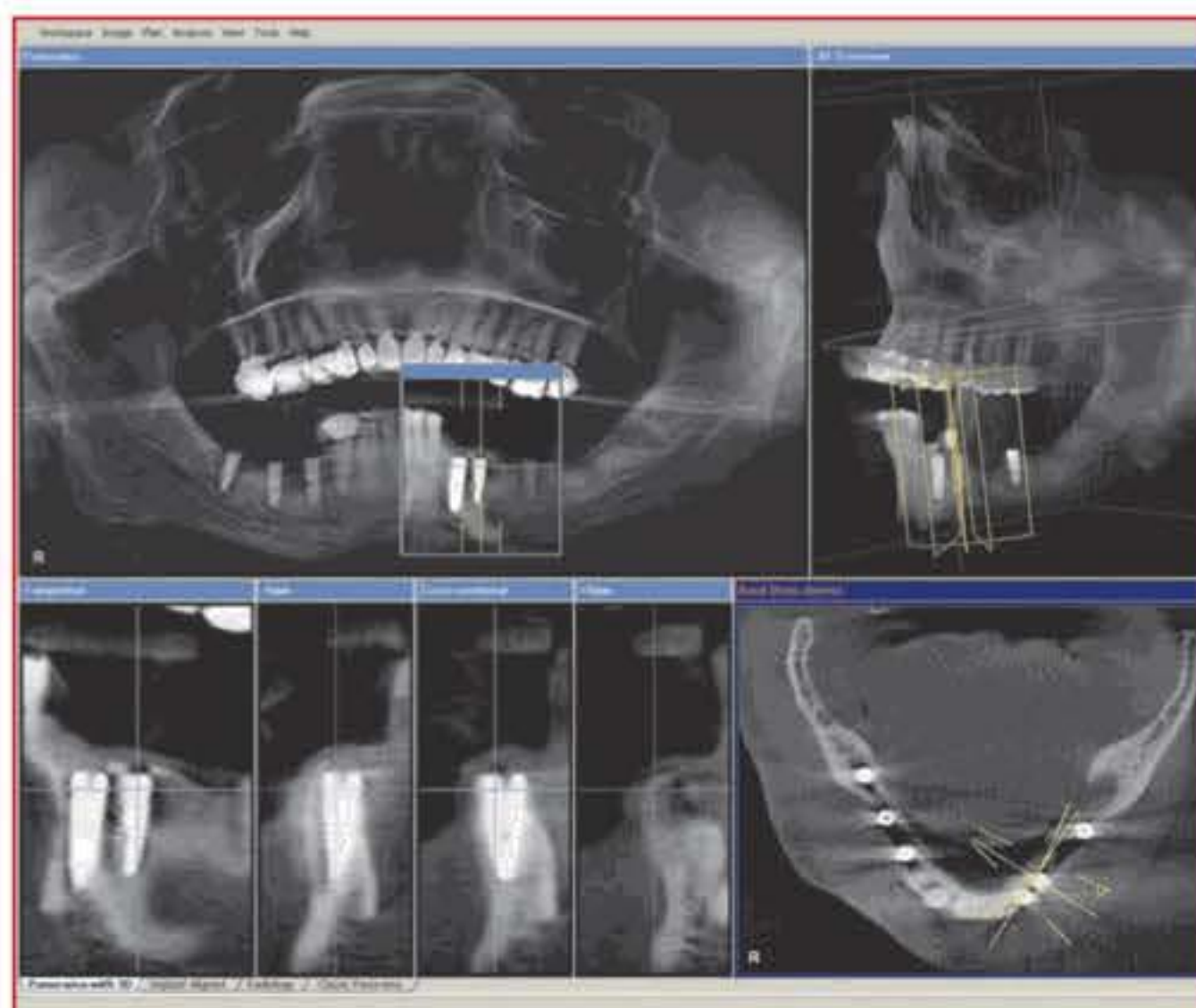




Fig 14-16 Implant planning in region 13 with sufficiently broad alveolar ridge for insertion of a D3.4 L13 implant with adequate vestibular and palatal bone coverage.



Fig 14-17 Positioning of the implant in region 23 with reduced bone availability, protecting the vestibular cortical bone, particularly considering the convex retraction toward the nasal spine typical in the maxilla.

14.2.3 Implantation into the Anterior Maxilla

In implant insertion in the anterior maxilla, the esthetic aspects of the prosthetic device generally receive the greatest amount of attention. Patient expectations are extremely high, particularly where there is a high smile line and small spans, since it is expected that the contours of the crowns and the soft tissue will be restored to their appearance before the tooth loss. This requires precise diagnostics so that the implants can be placed at the level of the cemento-enamel junction of the adjacent teeth and in the correct orovestibular position.

For edentulous patients, the implant prognosis significantly depends on the bone structure and bone availability in the anterior maxilla (Figure 14-6). If there is too little bone availability, both from a quantitative and a qualitative point of view, it has been shown that it is preferable to place implants by performing a sinus floor elevation in the posterior tooth area for anchoring the tooth replacement. In particular, the contour of the bone with respect to the nasal spine frequently results in retractions that result in inadequate bone coverage of the implants and thus limit the prognosis (Figure 14-17).

14.2.4 Implantation into the Posterior Maxilla

Implantation in the maxillary posterior area requires consideration of the maxillary sinus findings during planning (Figures 14-18 to 14-21). In the beginnings of modern implantology, attempts were made for optimal utilization of existing bone via short implants; however, today it is routine to raise and build up the maxillary sinus floor (sinus floor elevation and augmentation). If there is a sufficient bone bed, a minimally invasive sinus lift can also be done via crestal access, using osteotomes – also called bone condensers (Figure 14-22). The correct estimation of bone quality is crucial in this context, since implant loss can occur through compression-related osteolysis if the

Fig 14-18 A CBVI image with conventional drilling template with sleeves for possible implant insertion in regions 17 through 27 in the maxilla and in regions 35 through 45 in the mandible. The vertical bone availability in region 26 is 11.2 mm, in a patient with chronic sinusitis.

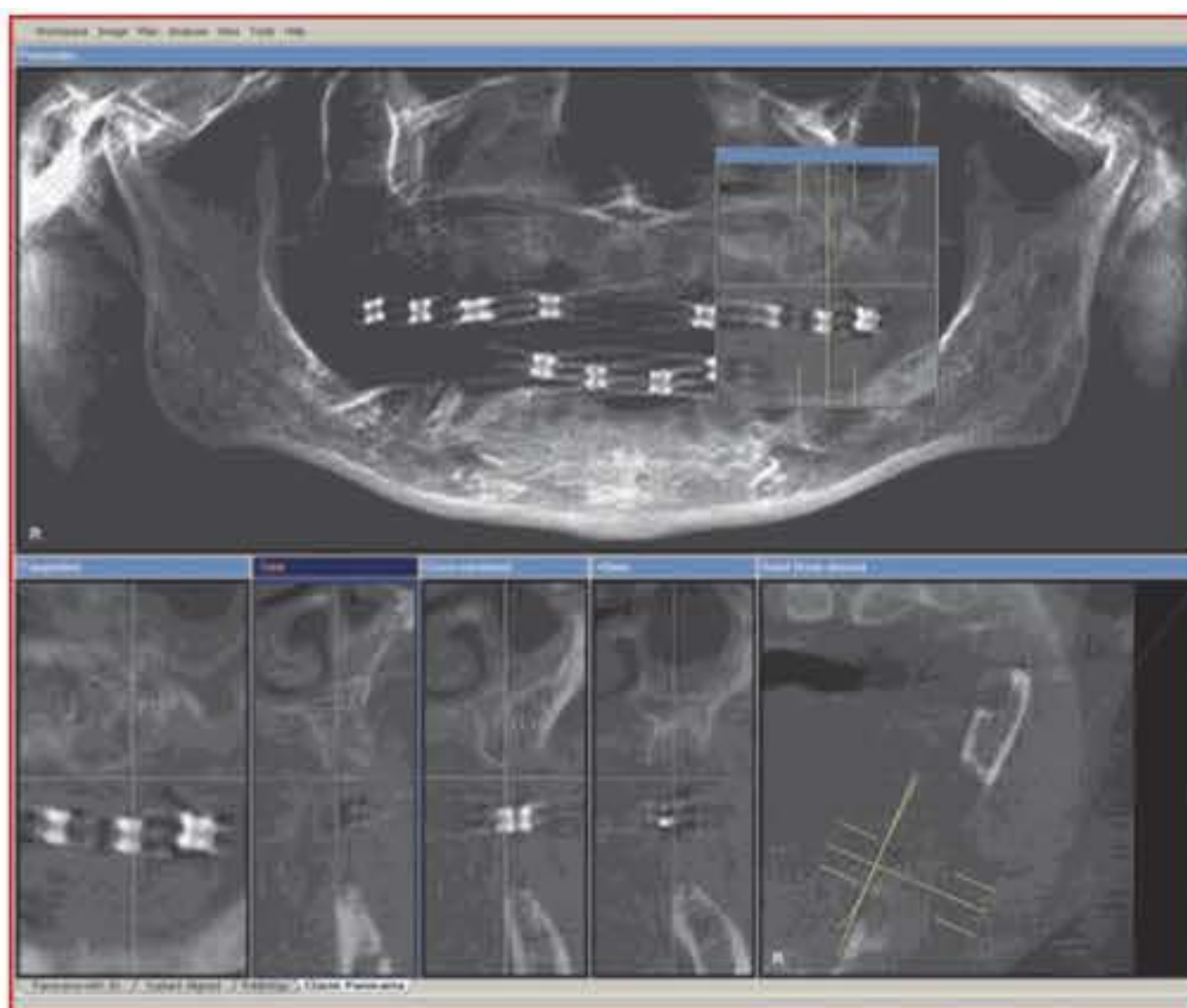
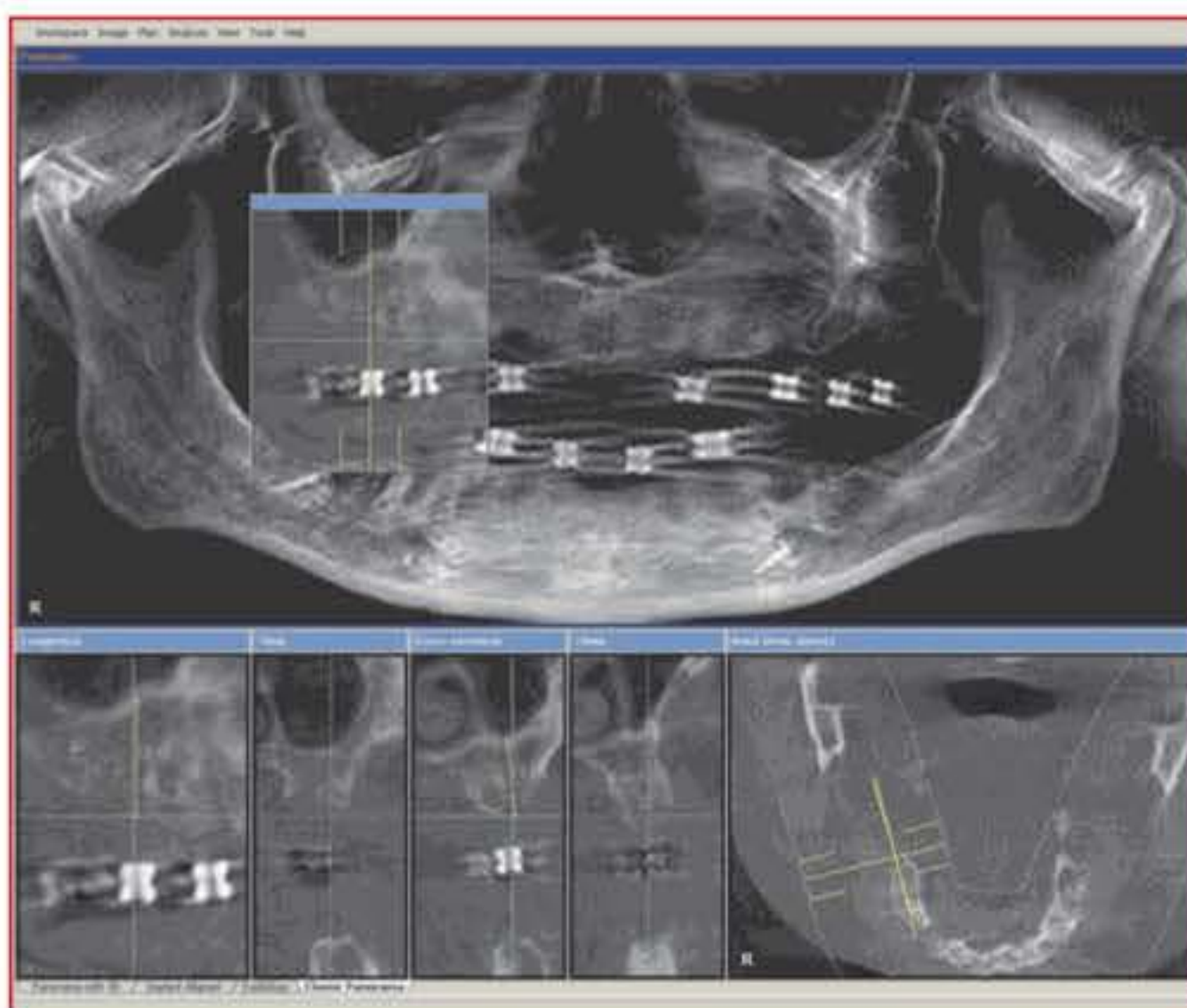


Fig 14-19 Bone availability of 13.8 mm in region 25 with slight crestal bone defect and necessary correction of the implant axis planned by the dental technician.



Fig 14-20 Planned implant insertion in region 16 with 13.5 mm of bone availability and optimally positioned drill sleeve.



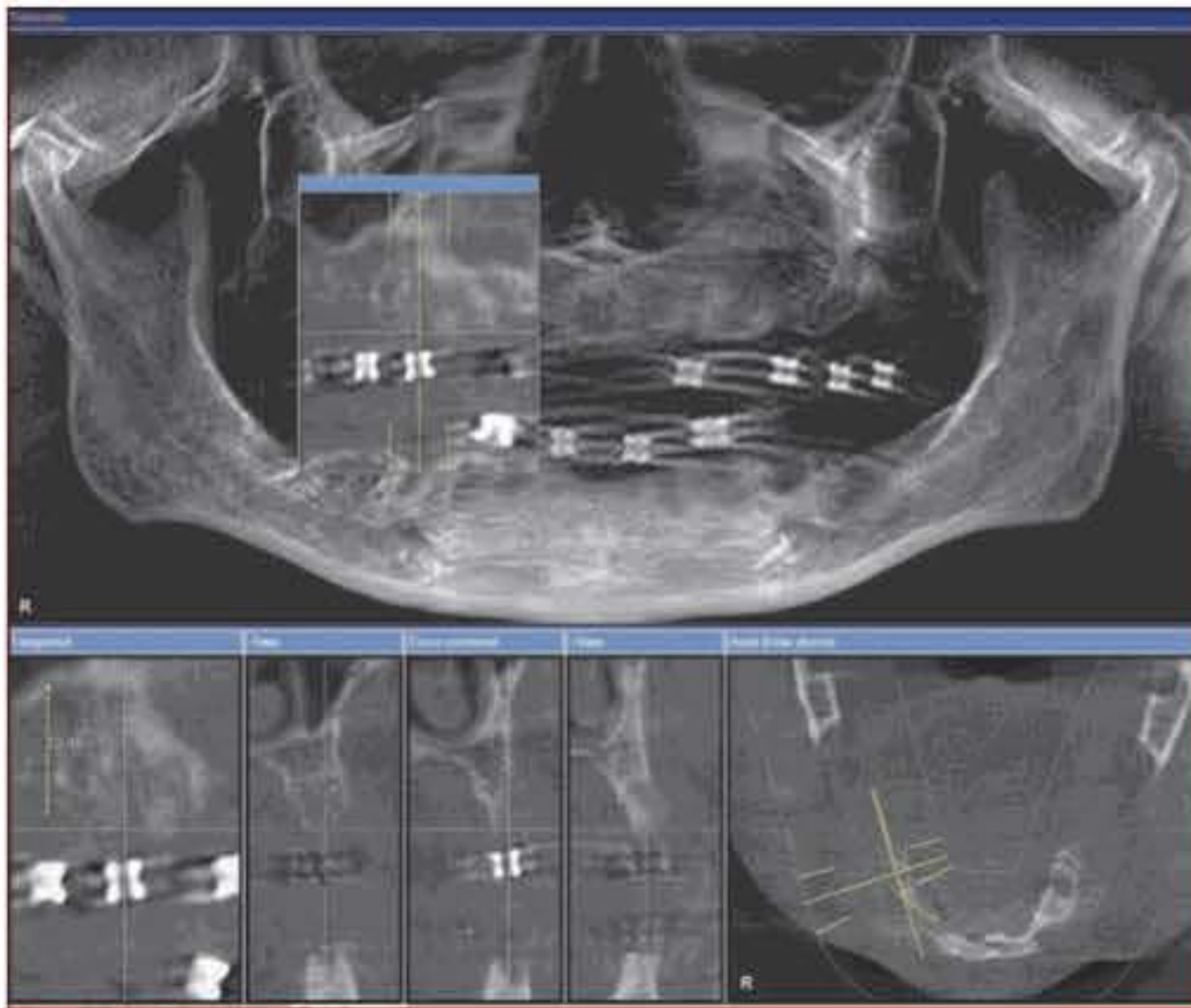


Fig 14-21 Pronounced defect in region 15 requiring augmentation using bone chips and stabilization with a membrane.

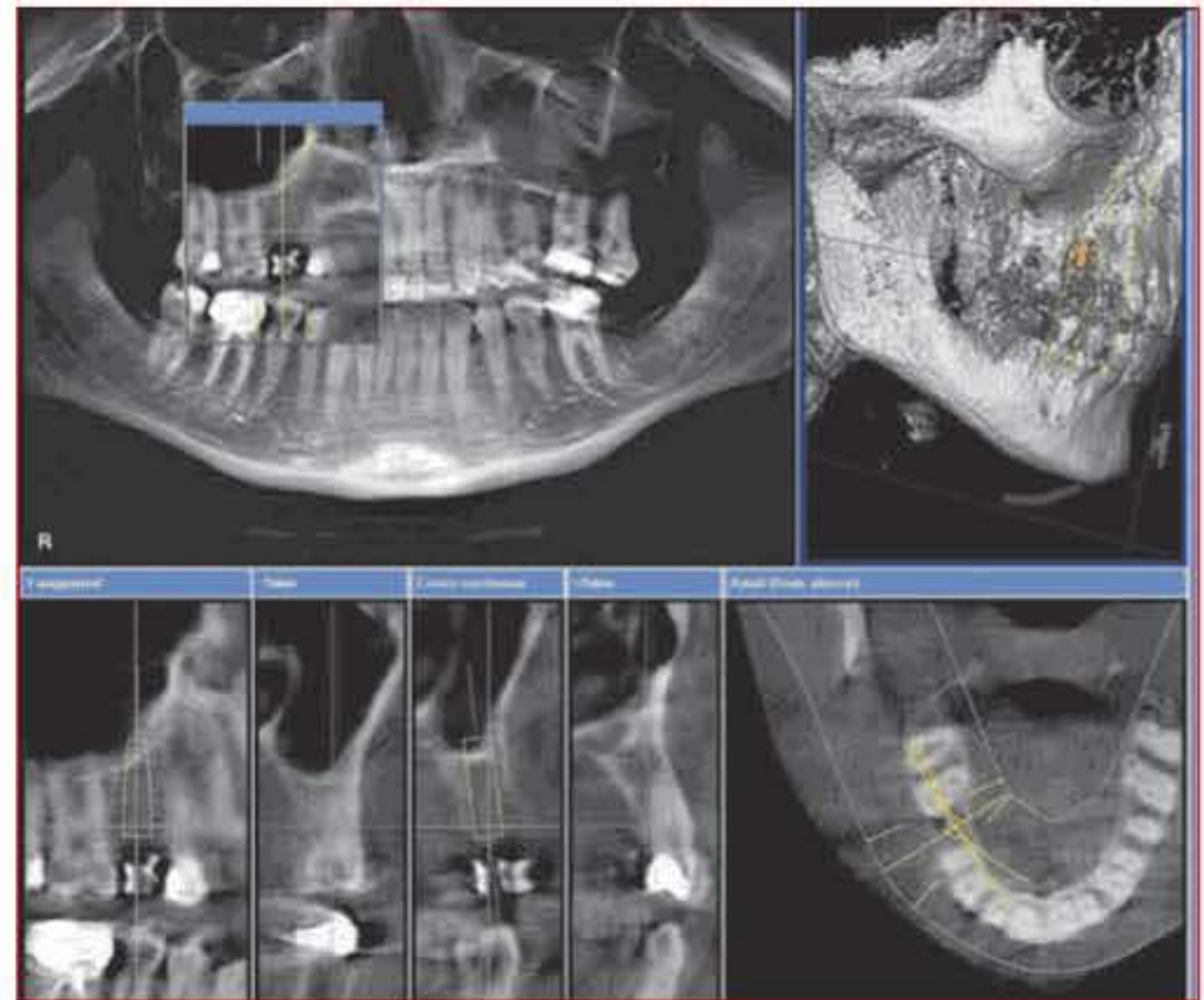


Fig 14-22 Individual missing tooth in region 15 with vertical bone supply of 10 mm, cortical structure in the area of the maxillary sinus floor and finely meshed spongiosa. The insertion of an individual implant is planned, including an internal sinus lift via bone condensing.

compact structure is too dense. As an alternative to augmentation, a recent option has been described where implants are not placed along the axis, but along the existing bone availability at the edge of the maxillary sinus in the direction of the canine fossa and in the area of the tuberosity. This method involves a detailed procedure using preoperative CBVI diagnostics.³⁻⁵

14.3 Implantation with the Use of Augmentative Procedures

14.3.1 Local Augmentation

The long-term stability of an implant is determined by the bone availability at the time of insertion. If the implants are placed with a remaining bone of 1.5 mm vestibularly and orally, the risk of peri-implantation bone loss is low. Bone availability can be precisely determined using the measurement function in CBVI and the alignment of the implants can be finalized using 3D planning. This facilitates the preoperative evaluation of expected specific peri-implantar defects and the determination of the most suitable method for the situation (Figures 14-23 to 14-30).



Fig 14-23 Planning CBVI with prosthetic proposal in a patient with loss of teeth 15 through 13 and 23 through 25. The inadequate regeneration of the alveoli six months after tooth extraction is clearly revealed.



Fig 14-24 Implant planning with the need for a sinus floor elevation in region 15 to insert two implants on the right side of the maxilla.



Fig 14-25 Positioning of implants in region 23 with bone defect and in region 25 with a well-developed alveolar ridge.

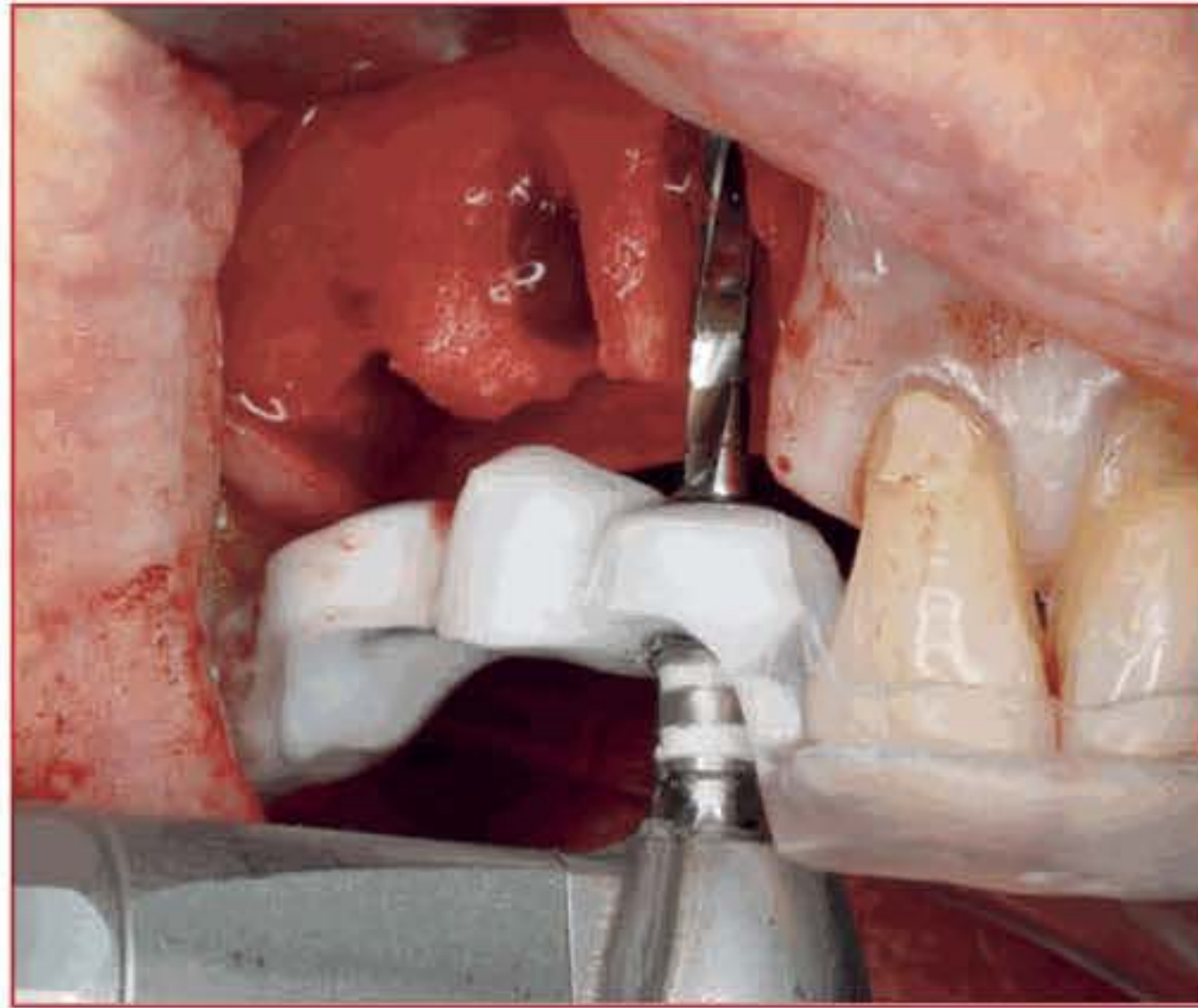


Fig 14-26 Clinical situation with incompletely regenerated alveoli, which had already been diagnosed radiologically; a pilot hole was drilled using drilling template.

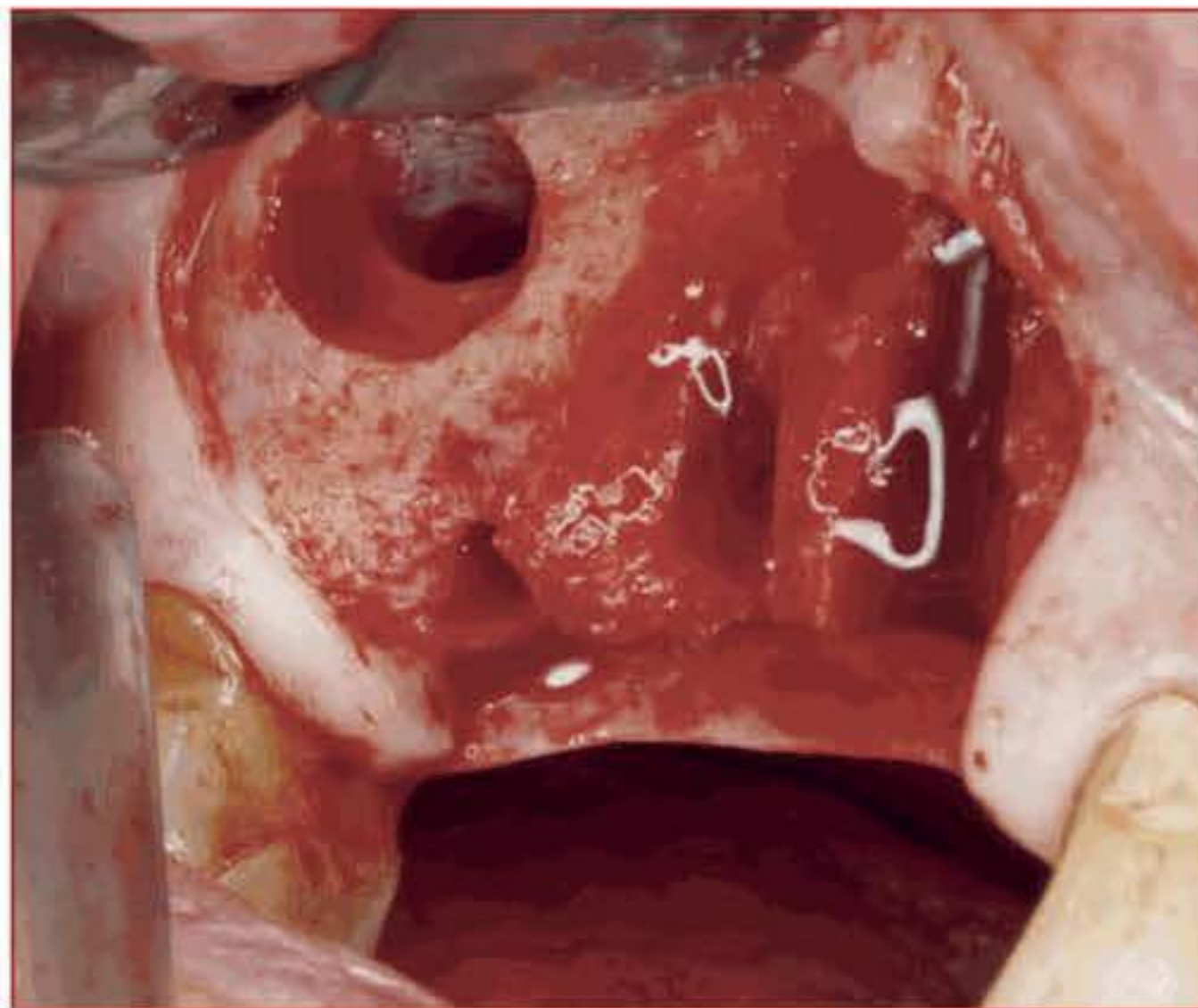


Fig 14-27 Preparation of implant cavity and complication-free elevation of the maxillary sinus membrane in region 15.

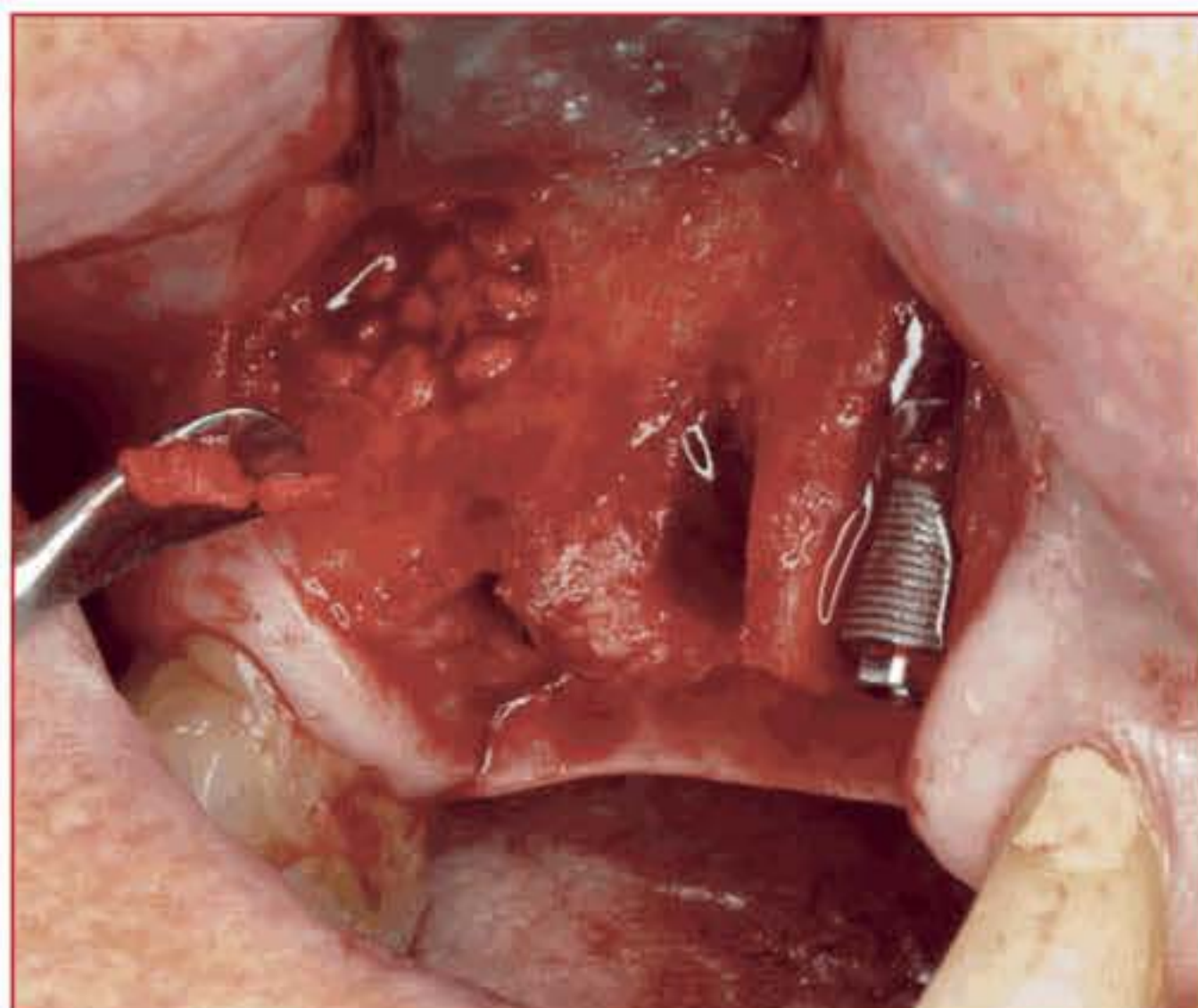


Fig 14-28 Insertion of two Templant implants (Medentis, Bernau) after sinus elevation in region 15.

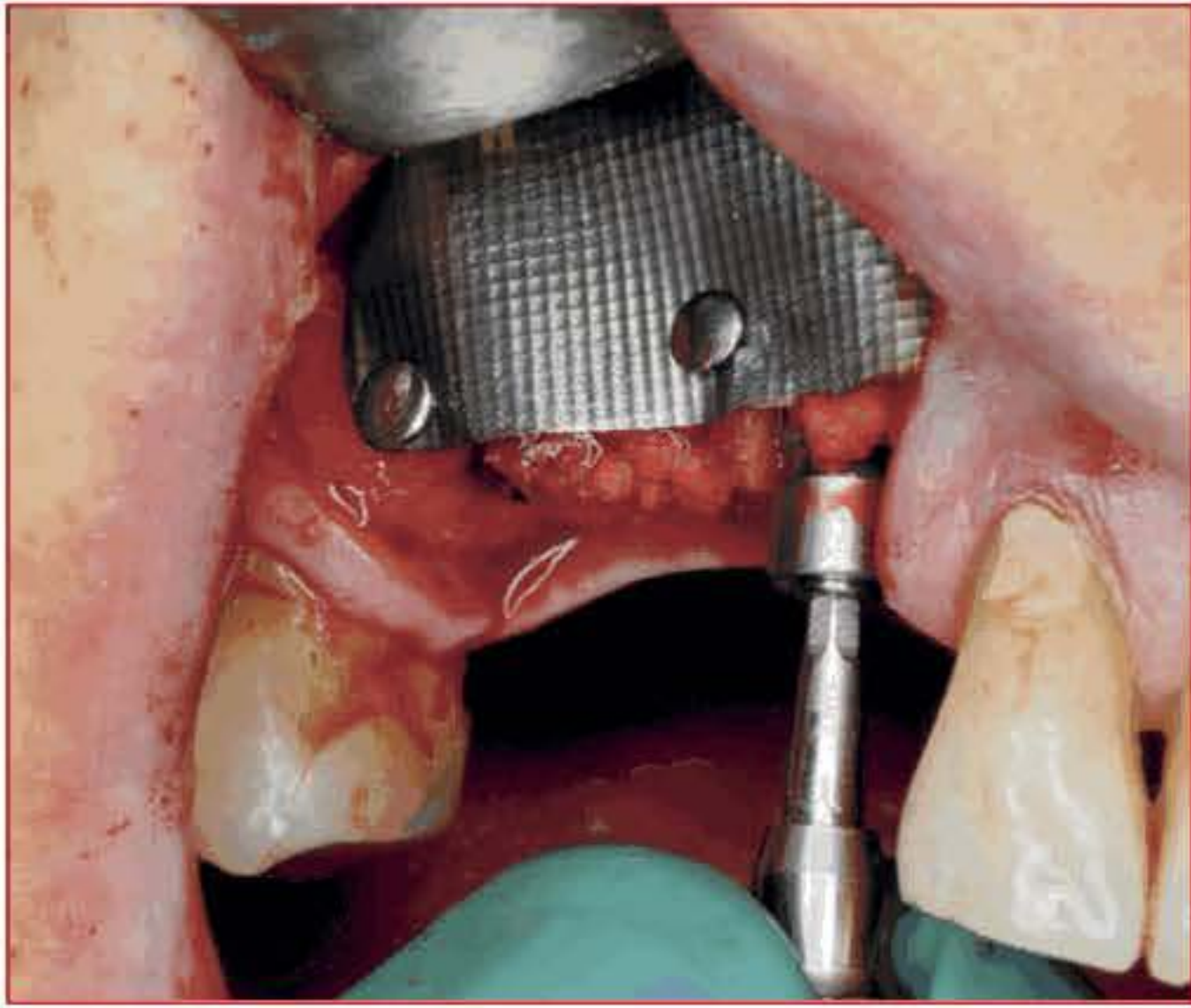


Fig 14-29 Stabilization of maxillary sinus floor augmentation with grafting material and stabilization of the vestibular defects with a titanium membrane.

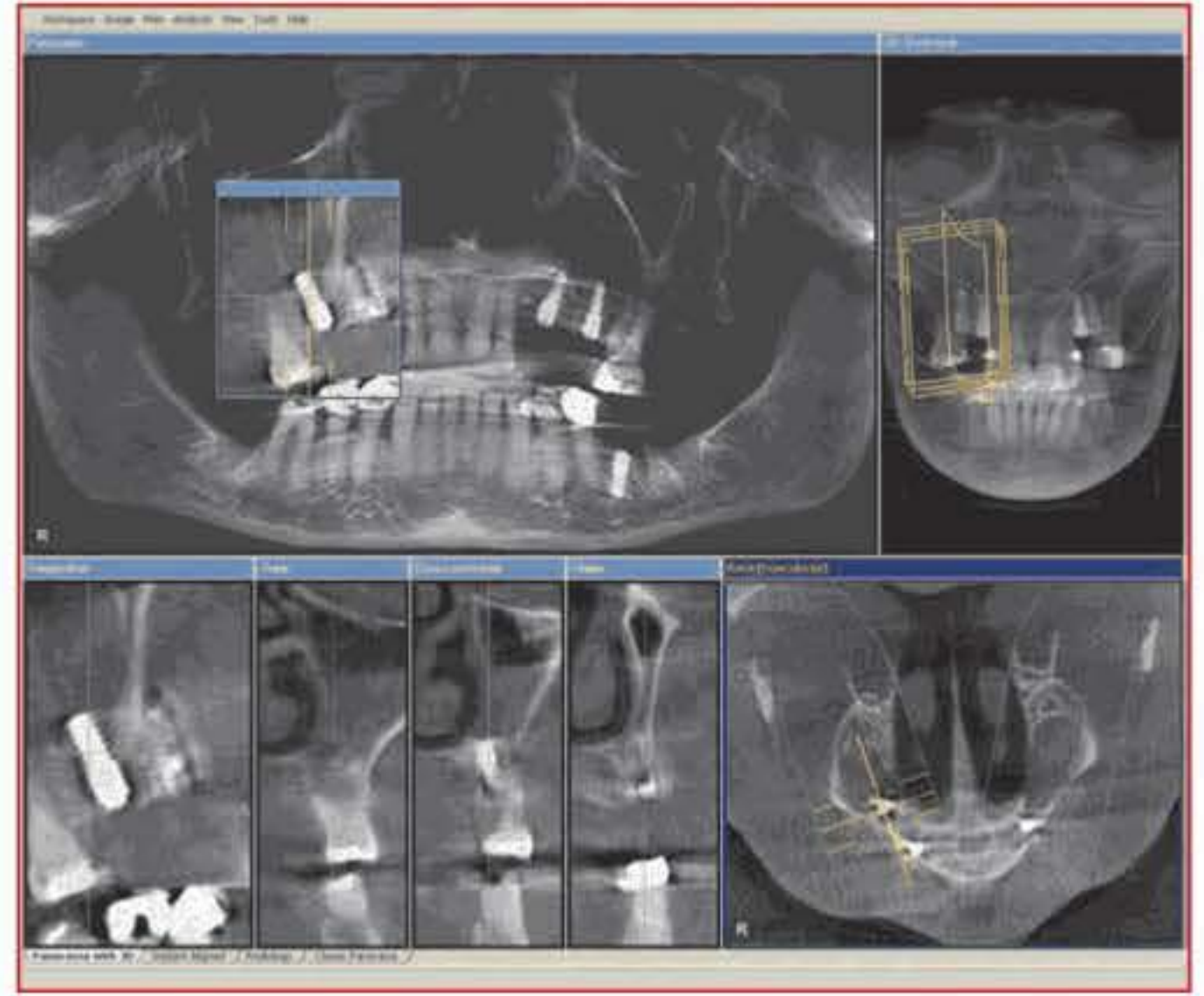


Fig 14-30 Control image after insertion of five implants and complication-free sinus floor elevation and augmentation.

14.3.2 Intraoral Grafting

If intraoral bone removal is necessary, preoperative diagnostics is required at both the donor and the recipient site. As CBVI displays the entire anatomy of the visceral cranium, the best donor area can be selected to build up the defect. For intraoral bone harvesting, the following donor areas are recommended: chin, tuberosity, zygomatic alveolar crest and retromolar region with the ramus. Using a donor site from the chin area permits a large volume of bone to be removed, but there is high postoperative patient morbidity owing to the sometimes slow recovery from the sensitivity impairment.⁶ The tuberosity yields a small bone volume with soft bone quality. The zygomatic alveolar crest is mainly suited for bone removal via piezosurgery, when only bone chips are to be harvested.⁷ However, the maxillary sinus should not be opened in the process. Bone availability can be precisely determined using CBVI.

In intraoral block bone grafts, the exact extent of the defect must be determined during preoperative diagnostics to establish the size of the graft, and the bone availability at the donor site must also be determined. In retromolar bone block removal, patient morbidity is relatively low.⁸ However, there is a risk of damaging the inferior alveolar nerve, especially when a large volume of bone is harvested. The vertical and horizontal course of the nerve can be precisely determined using CBVI, thus reducing the risk of possible loss of sensitivity (Figure 14-31). At the recipient location, CBVI also provides sufficient information on the quality of the local bone that is needed to anchor the osteosynthesis screws, so that a good consolidation of the transplanted bone is achieved (Figure 14-32).



Fig 14-31 Detailed representation of bone donor site with incipient recontouring of the defect at the time of implant planning in the maxilla, also revealing a significant distance to the inferior alveolar nerve.



Fig 14-32 Radiological check-up three months after retromolar bone transplantation in region 11, with good bone regeneration and no recognizable bone resorption at the head of the osteosynthesis screw.

14.3.3 Sinus Floor Elevation

In sinus floor elevation, an extremely careful preparation of Schneider's membrane is required in order to prevent its perforation. Consequently, it is important for the surgeon to be aware of the dimensions of the facial maxillary sinus wall before commencing. Existing 2D radiological techniques do not provide any valuable information in this respect. As the surgical procedure continues, information on the profile of the maxillary sinus floor is also important. With precise knowledge of the contour of the maxillary sinus floor, the mucosal membrane can be carefully and confidently prepared since there are no surprises in the form of unrecognized small septa or areas that pass under.⁹ For the subsequent implant placement, a sufficiently sized bone bed is necessary for stable insertion of the implants. Use of 3D imaging facilitates a preoperative decision for a one- or two-stage procedure, and thus informs the patient's expectations regarding the operative results (Figure 14-33). In this way, crestal bone defects can be recognized prior to the surgery, and the scope of the operation can be precisely determined in consultation with the patient. Preoperative radiological findings of this type allow precise surgical planning and facilitate the surgical course occurring according to plan (Figure 14-34).

For difficult anatomical relationships with fine septa, the patient can be informed in detail regarding the risk of a perforation of Schneider's membrane. The 3D implant planning then facilitates the optimal utilization of the existing bone supply for implant placement with high primary stability (Figure 14-35). Implant insertion with simultaneous sinus augmentation is much safer if carried out in this way and it can also be done in less operational time since the surgeon is able to deal with the specific anatomy prior to the surgery, rather than first encountering it intraoperatively (Figure 14-36). As precise anatomical information is available, the augmentation can then be performed in the complete area of the maxillary sinus floor, without risking remaining pseudoresidues with the associated potential for cyst formation.

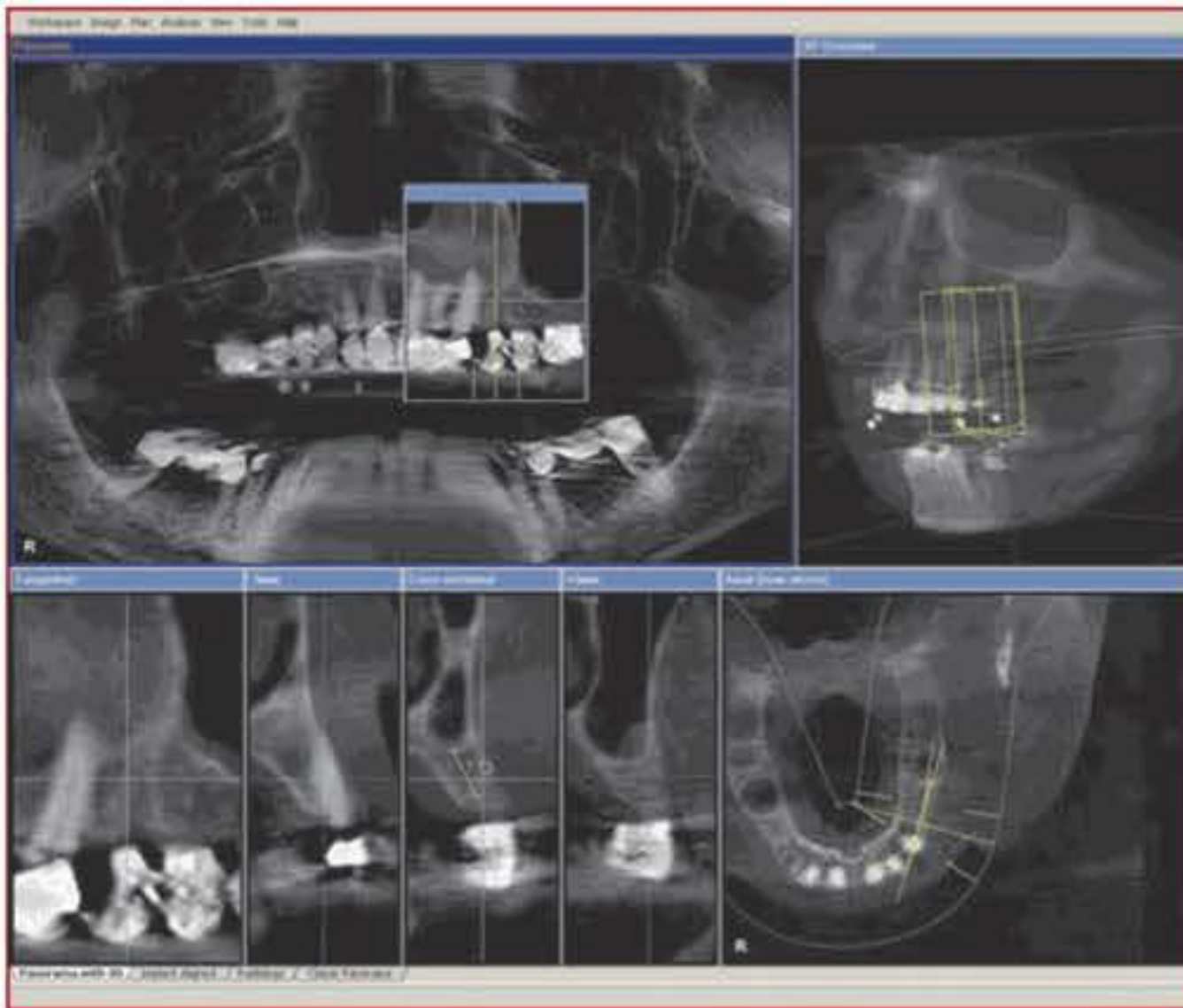


Fig 14-33 Planned implant insertion in region 24 with uninflamed maxillary sinus mucosa and vertical bone availability of 7.7 mm, providing ideal conditions for one-stage implantation.

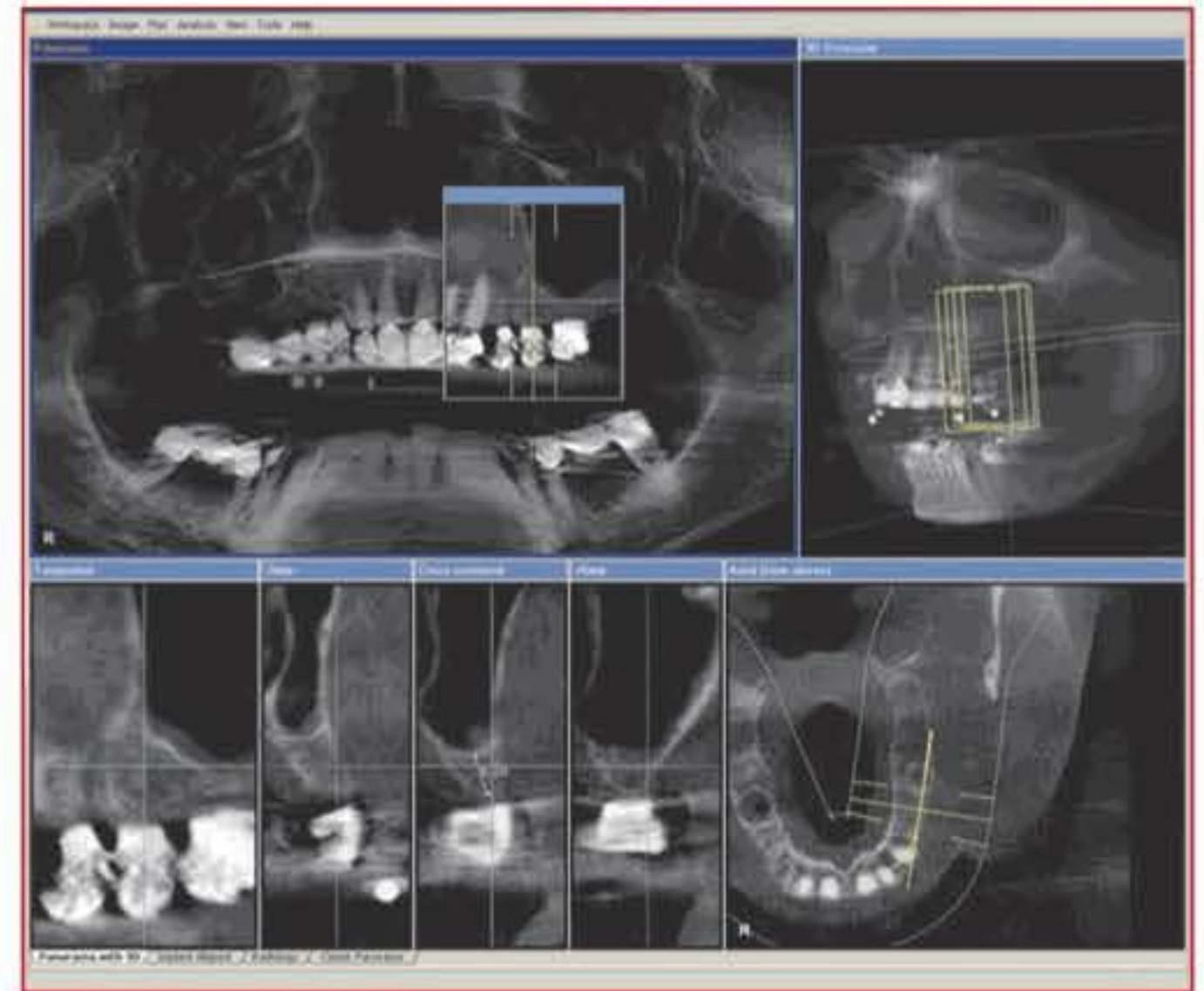


Fig 14-34 Reduced bone availability of 6.3 mm for planned one-stage sinus lift with limited extent of chronic mucosal swelling in region 25.

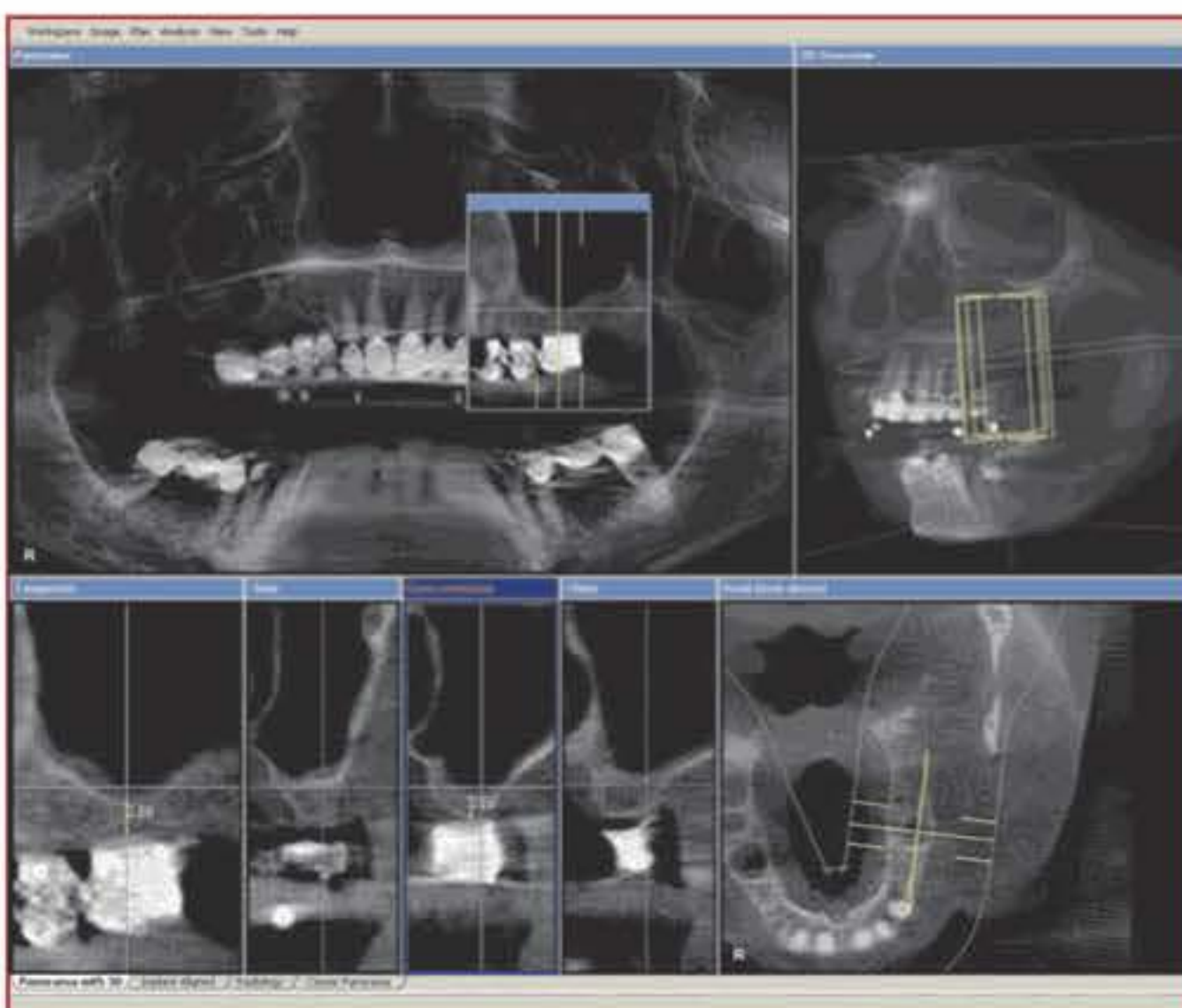


Fig 14-35 Limited remaining bone availability of 2.7 mm with reduced possibility of primary stable implant anchoring in the primary implant insertion.

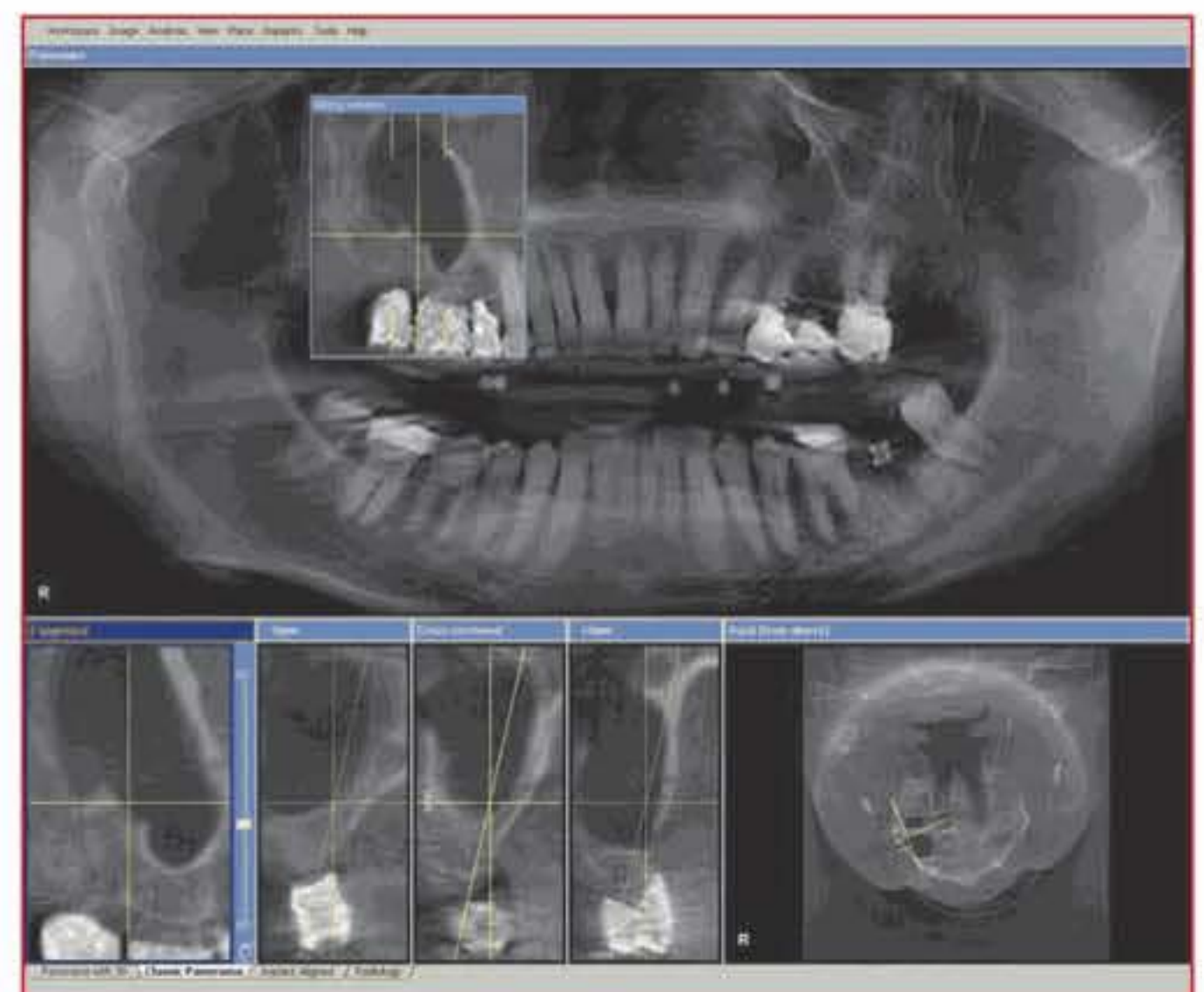


Fig 14-36 Uninflamed maxillary mucosal membrane in a planned sinus floor elevation on the right side of the maxilla; display of two septa of different heights. The preoperative imaging of the lower septum facilitated careful elevation of the mucosa.

14.3.4 Extraoral Grafting

Significant defects (e.g. following trauma or atrophies) that exhibit nearly complete loss of the alveolar process require vertical and horizontal augmentation (Figure 14-37). This can be accomplished most safely using free grafting of strips of monocortical bone from the anterior iliac crest, with vestibular incision.¹⁰ Following such a comprehensive augmentation, the natural points of orientation for implant planning are no longer available. In this case, 3D implant planning using a prosthesis proposal to include the augmentation is particularly helpful for ensuring insertion of the implants at the prosthetically correct position (Figures 14-38 to 14-42).



Fig 14-37 Pronounced atrophy after many years of incorporation of tegu-mental dentally supported tooth replacement, with successive loss of the abutment teeth located at the end of the dental arch.

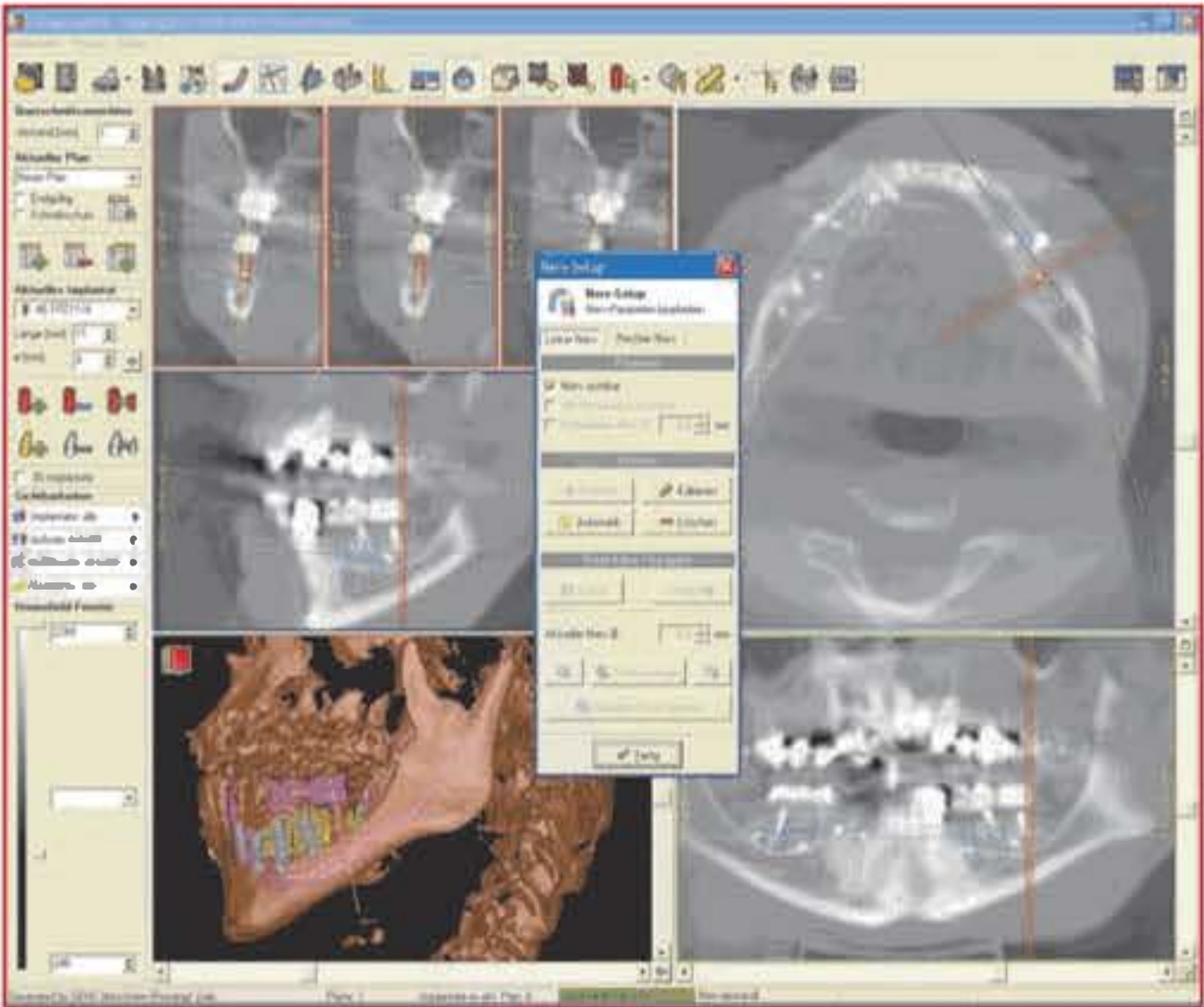


Fig 14-38 Planning with the Codiagnostix device after successful iliac crest transplantation with multiple monocortical strips from the pelvis.

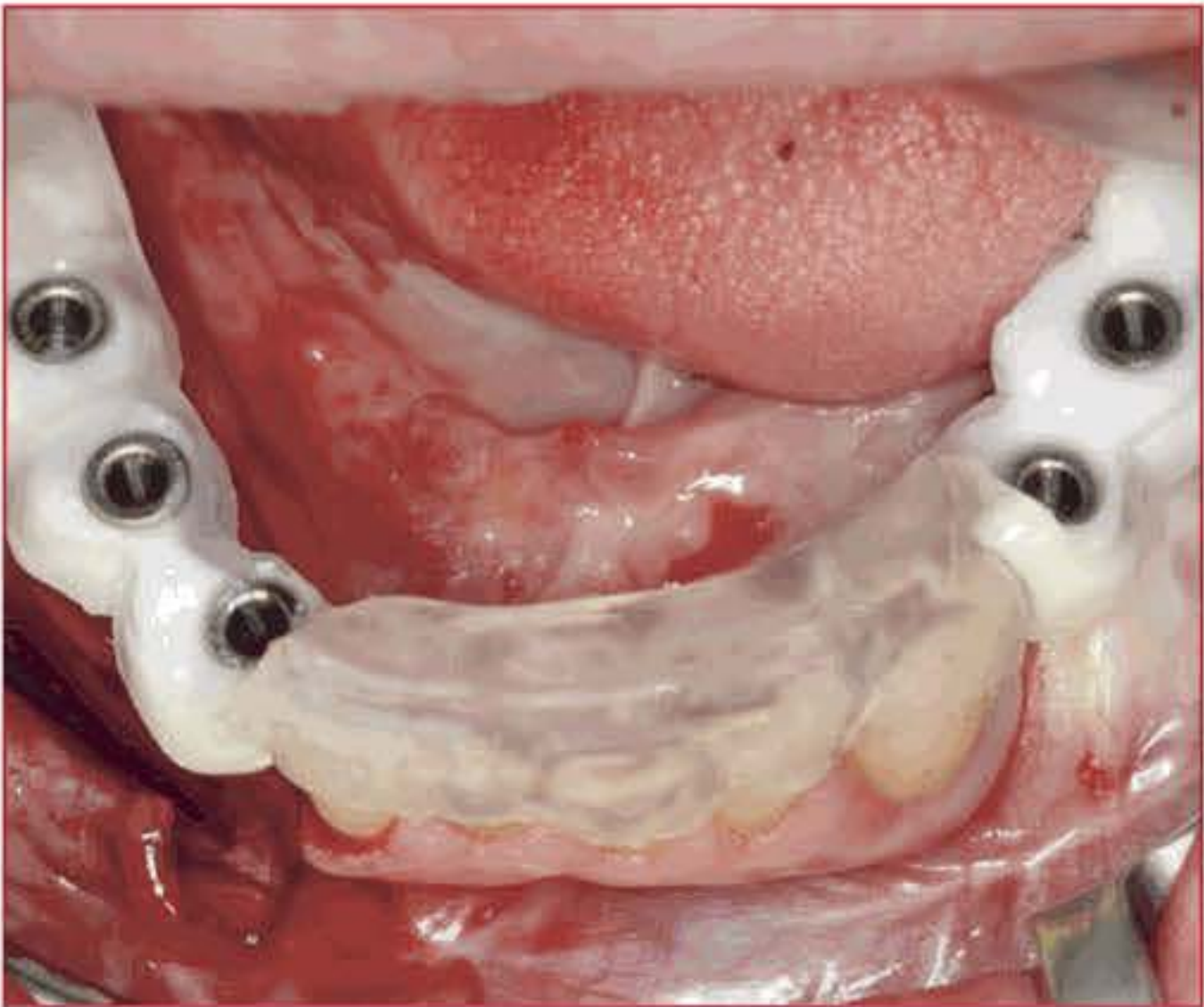


Fig 14-39 Positioning of a posterior-produced surgical guide with the posterior drill sleeves for pilot drilling.

Fig 14-40 Postoperative check, revealing the nerve profile with an implant position extremely close to the mandibular canal, but showing no nerve compression.



Fig 14-41 Positioning of straight standard suprastructures for incorporation of the fixed restoration with splinted crowns.



Fig 14-42 Reconstruction of support zones in the mandible using implant-supported tooth replacement.



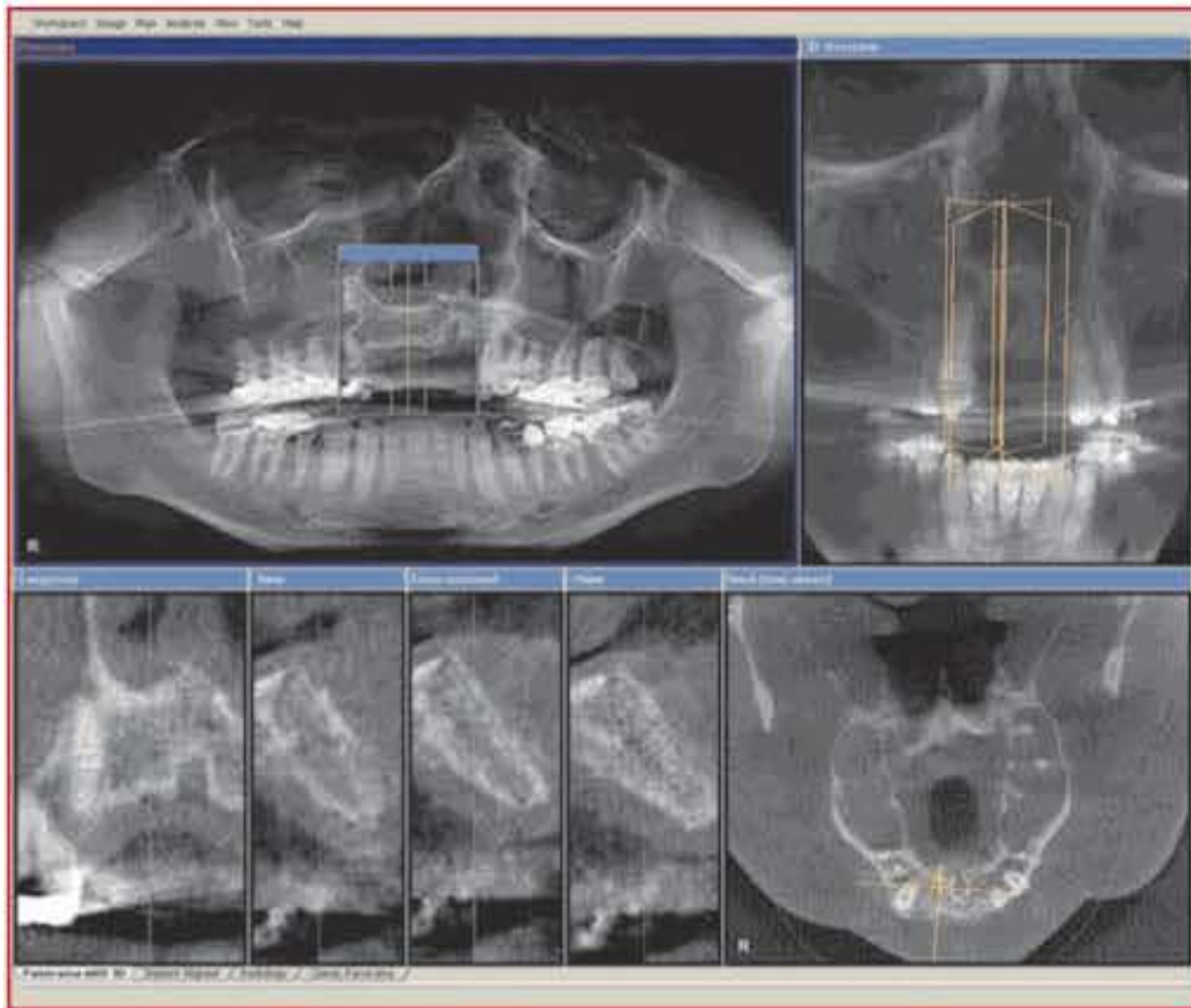


Fig 14-43 Radiological representation of a pronounced alveolar ridge defect in the maxilla after dentoalveolar trauma.



Fig 14-44 Clinical situation with indicated incision for carrying out a distraction osteogenesis.

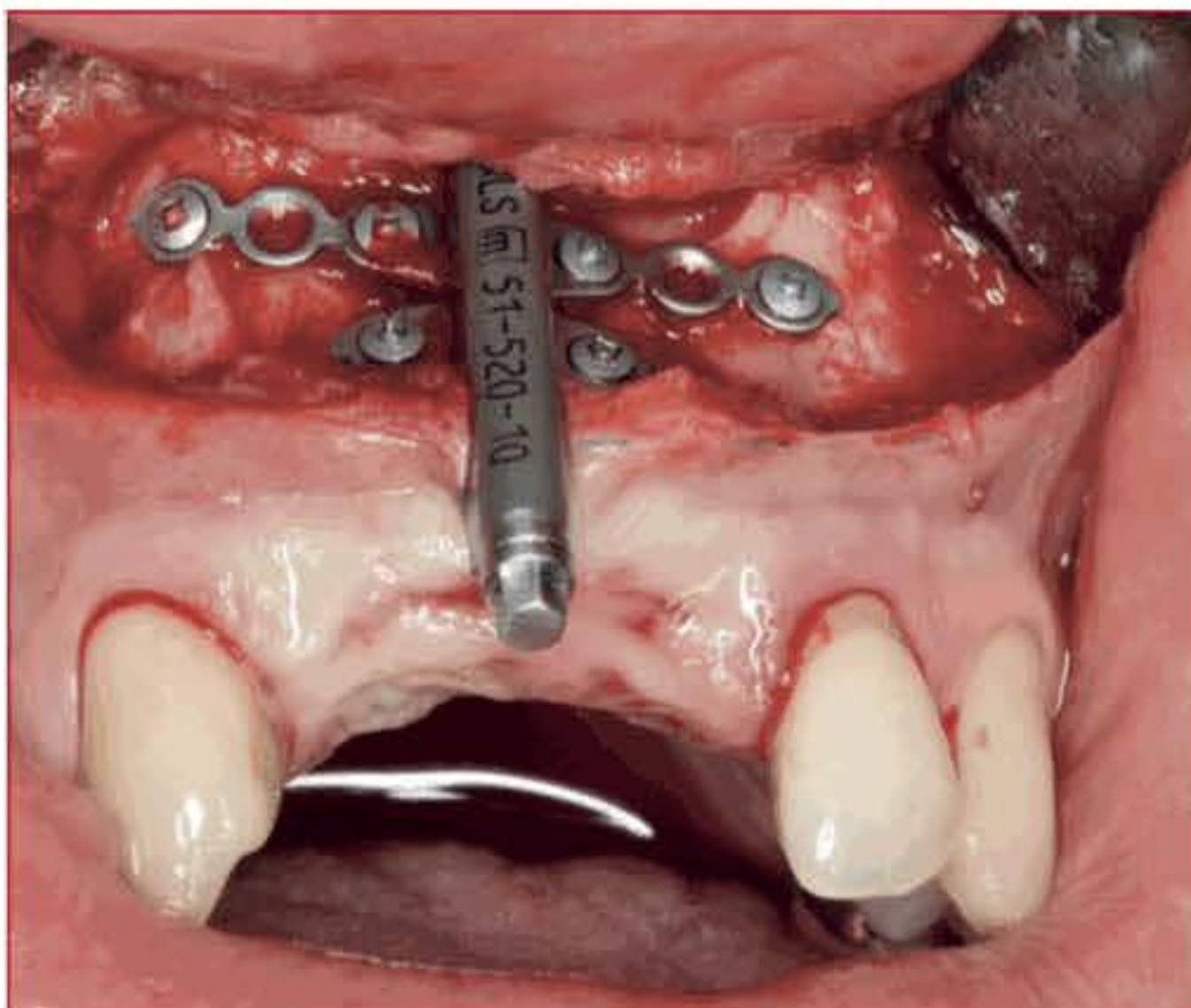


Fig 14-45 Intraoperative situation after successful segment osteotomy with applied distraction device.

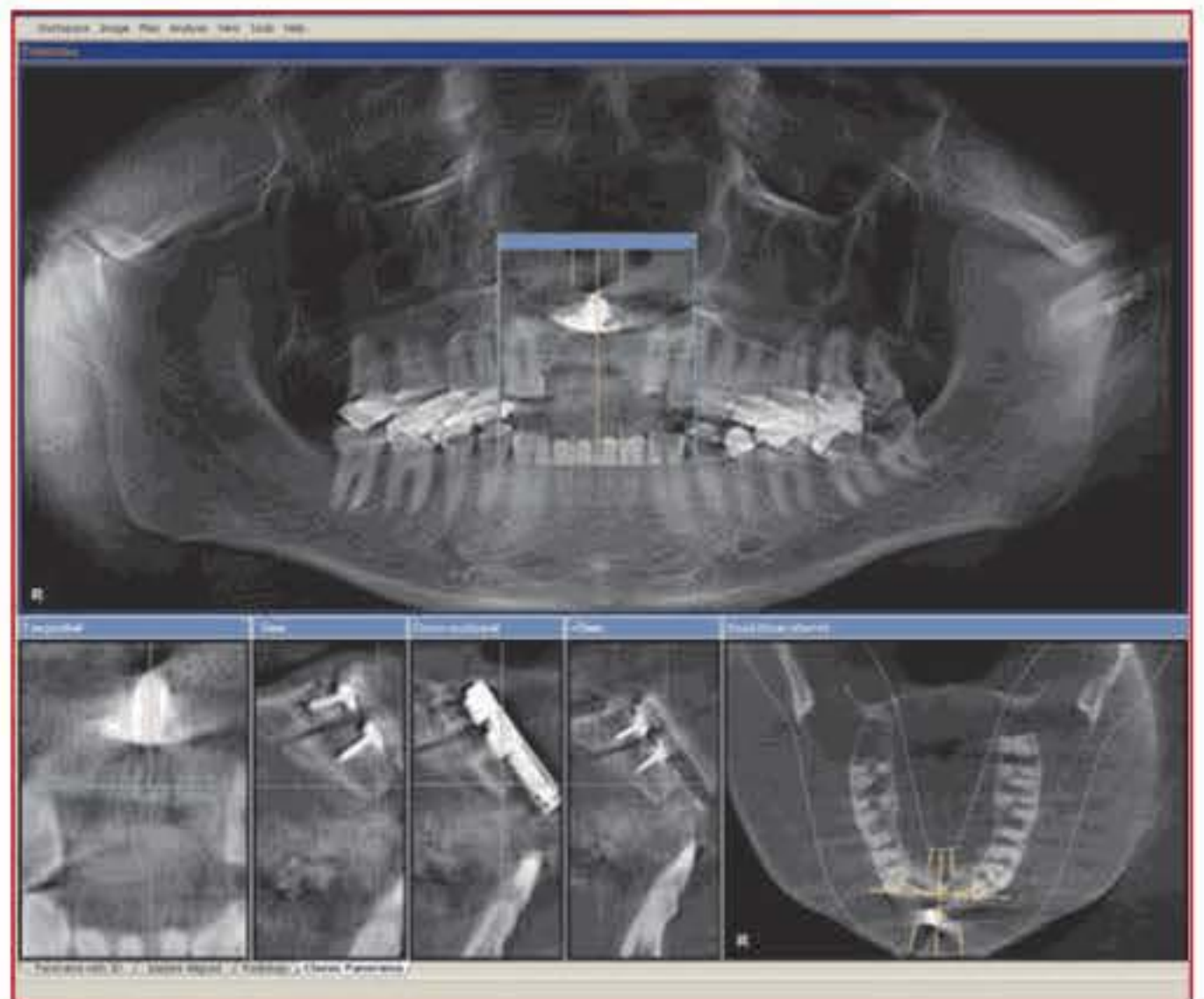


Fig 14-46 Radiological check of the segment osteotomy and the application of the distractor using CBVI, revealing a sufficiently stable base without damage to adjacent anatomical structures.

14.3.5 Distraction

Alveolar process distraction permits the repair of vertical defects of the alveolar ridge (Figures 14-43 to 14-46).¹¹ In distraction osteogenesis, the crestal segment is loosened in an osteotomy and freely moved by the distractor. For implant planning, it is important that the implant position is selected such that the transported segment is also supported by the implant, in addition to considering the prosthetic aspects. Since the osteotomy line does not always run parallel to the occlusal plane, 3D diagnostics provides precise information on the profile of the local bone and facilitates an implant plan in which apical implant support is provided in the local bone for a stable long-term prognosis (Figures 14-47 and 14-48).

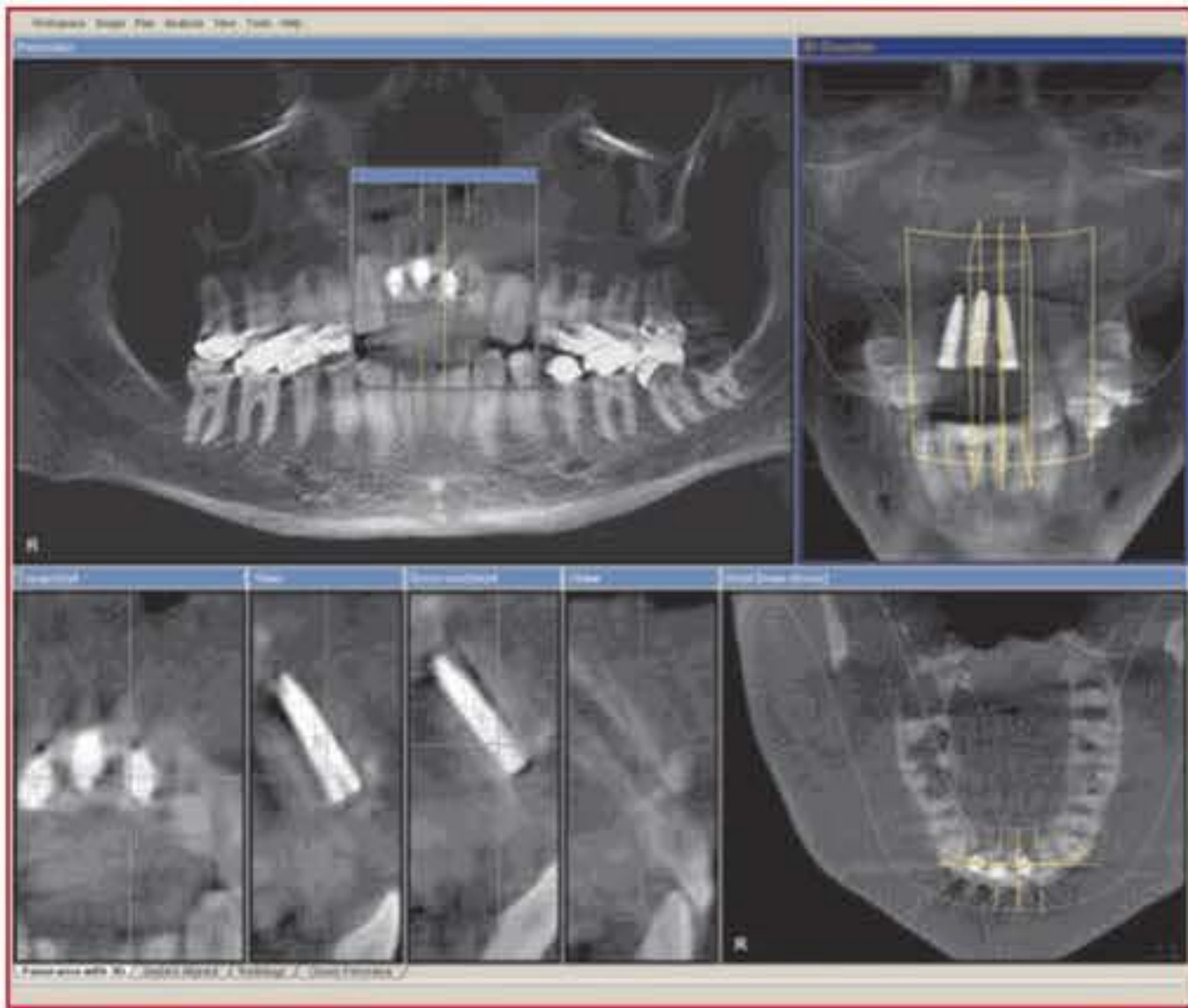


Fig 14-47 Postoperative implant check with anchoring of the implants in the local bone over the callus area.



Fig 14-48 Definitive prosthetic accommodation with contouring of the soft tissue.

14.4 Implementation by means of Computer-aided (CAD/CAM) Surgical Guides

If 3D image data and virtual implant planning are available, a CAD/CAM surgical guide allows these to inform the surgical procedure.

Since 1997, there have been programs for computer-aided implant planning characterized by their ability to implement computer-generated plans intraoperatively using navigational methods (Simplant, Materialize, Belgium).¹² Different types of systems exist.

Stereolithographically created surgical guides are based on rapid prototyping technology and require exact 3D data on the anatomy of the patient, which are generated either directly from the patient's radiograph or from x-ray images of a wax-up. The later support surfaces for the surgical guide must be clearly identifiable in the image for stereolithographically generated surgical guides. This is the only way for a precisely fitted virtual 3D model of the guide to be created on the computer. These virtual models are then used for construction by a rapid prototyping machine.

Other systems spatially associate a plaster model or a corresponding template to a drill, so that the planned drill axis can be transferred to the template. This is done either manually using corresponding positioning devices¹³ or with an automatic CAD/CAM drilling unit.¹⁴

However, a disadvantage of many such systems is that different individual components have to be used for imaging, planning software and hardware.¹⁵ This results in additional interfaces for patient handling since radiology also has to be incorporated into the process chain, in addition to the treating surgeon, dentist, prosthodontist and dental technician.¹⁶ Furthermore, all components being used must be optimally coordinated with one another and also be completely understood by the user. In addition, it has been shown that radiologists are only partially aware of some of the special issues for dental diagnostics.

The workflow requirements and the sometimes high investment costs for imaging and for planning software have resulted in a rather hesitant use of this technology to date.



Fig 14-49 Pronounced alveolar process defect in a complex midfacial fracture and second-degree craniocerebral trauma. On the left side of the maxilla, an osteosynthesis plate is revealed through the mucosa.



Fig 14-50 Planning of alveolar ridge restoration using CBCT. Evaluation of a combined horizontal and vertical bone defect.

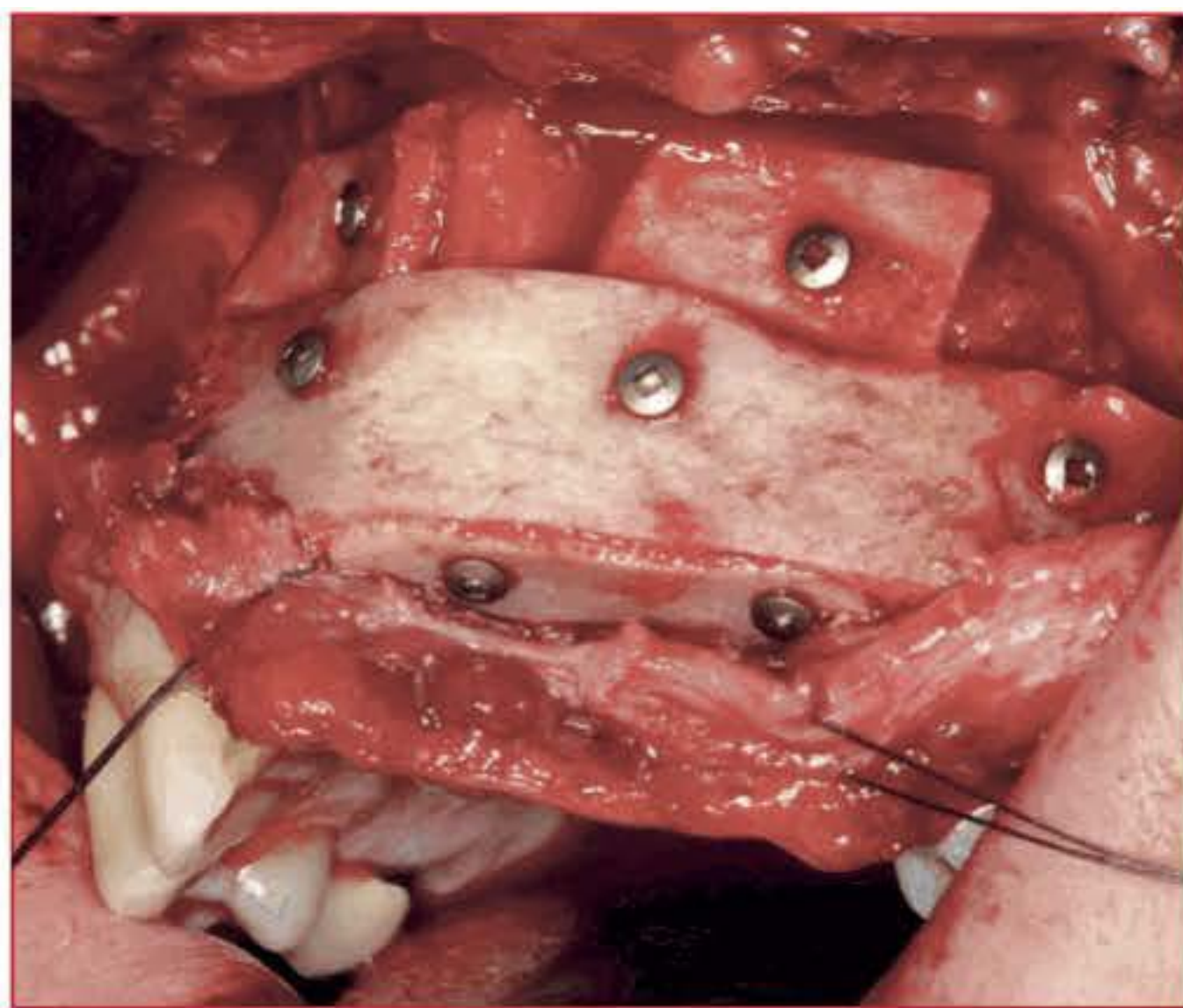


Fig 14-51 Intraoperative situation after alveolar ridge restoration using free bone grafting from the inside of the anterior iliac crest.

The following pathway was selected for the treatment process in implant planning using the GALILEOS system (Sirona, Bensheim, Germany). First, the dentist prepares the standard implant plan using an impression and bite registration of the patient (Figures 14-49 to 14-53). In the dental laboratory, a wax-up can then be prepared for the planned prosthetic tooth replacement (Figure 14-54). Depending on the scope of this prosthetic plan, it may be necessary to adjust it to fit the patient. After coordinating the procedure, the wax-up is transferred to an x-ray planning template in which the teeth are represented by barium sulfate-doped acrylic resin. Then, six marker balls are affixed to the system-specific reference plate; they are needed for the transfer between the individual work steps in the treatment procedure (Figure 14-55). When performing the scan, it is important to maintain a correct, reproducible position of the template in the mouth of the patient, as is true for all reference systems.



Fig 14-52 Postoperative situation after wound closure with vestibular incision and loss of the fixed mucosa in the area of the restored alveolar ridge.



Fig 14-53 Clinical situation 10 weeks after augmentation, at the time of planning the implant positions in regions 11 through 23 with loss of the gingivo-buccal fold.



Fig 14-54 Wax-up for the orientation of the prosthetic accommodations as a basis for the fabrication of a barium sulfate-doped x-ray template.

The scanned volume permits a complete evaluation of the entire visceral cranium. This obviates the accumulation of radiation exposure from several images when a large-scale oral rehabilitation is carried out. With this single image, the arrangement of the temporomandibular joint can also be evaluated, which can provide information on functional overloading and may identify necessary prosthetic measures. Upon receipt of the 3D data set, the implant position can then be freely selected in the planning window in accordance with the dental chart (Figure 14-56). After the implants are defined, the data volume is transferred to the central surgical guide fabrication process, which performs the pilot drilling in the plaster model or the reference plate using a five-axis milling machine (Figures 14-57 and 14-58). These pilot holes are then used to create the drilling template (Figure 14-59). Depending on the planned procedure, a provisional appliance is then produced with the aid of the planning model. Finally, the surgical guide is used to insert the implants (Figures 14-60 to 14-67).

The systems already established in the market for centralized surgical guide manufacturing via stereolithography require increased attention to segmentation, which is also done centrally to some extent.¹² In particular, the Nobel Biocare system requires a dual scan of the template or the prosthesis with reference marks, which means more radiological work, especially when this is carried out in a radiology center.¹⁷



Fig 14-55 Fitting of the x-ray template with the reference plate typical for the GALILEOS system with exclusively dental support.



Fig 14-56 Implant planning under consideration of prosthetic aspects with optimal positioning in the augmented alveolar ridge.

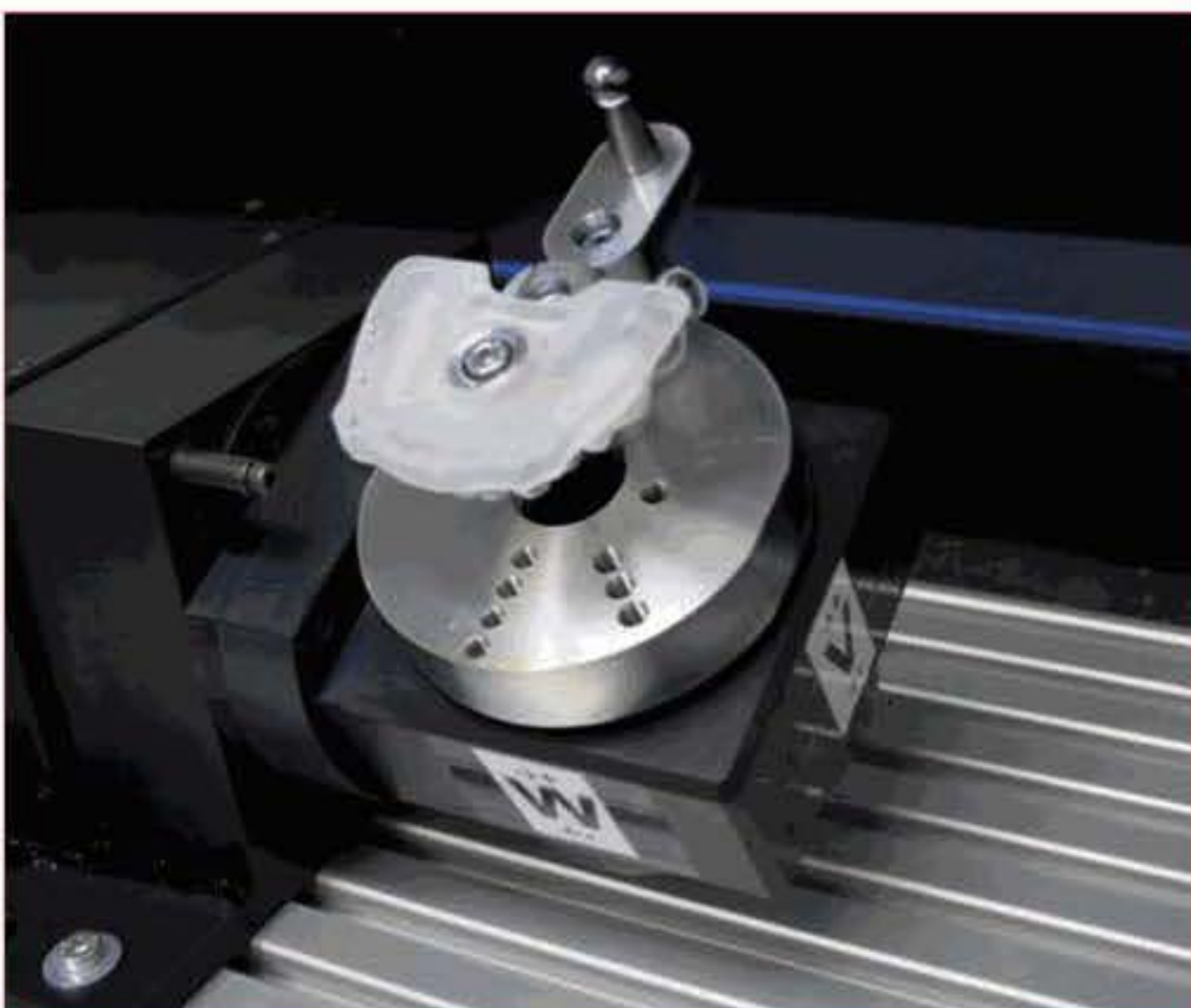


Fig 14-57 In the creation of the drilling template of the GALILEOS system, the x-ray template is first inserted into the computer-controlled five-axis milling machine. After detecting the registration markers, the mill carries out the drilling in accordance with the plan created in GALILEOS-Implant.



Fig 14-58 Calibration of the reference plate to check the drilling of the cavities in accordance with computer-assisted implant planning.



Fig 14-59 Technical modification of the x-ray template fabricated with CNC technology to create the surgical guide, with apical and crestal shortening of the barium sulfate set-up and placement of corresponding drilling sleeves into the CNC holes.

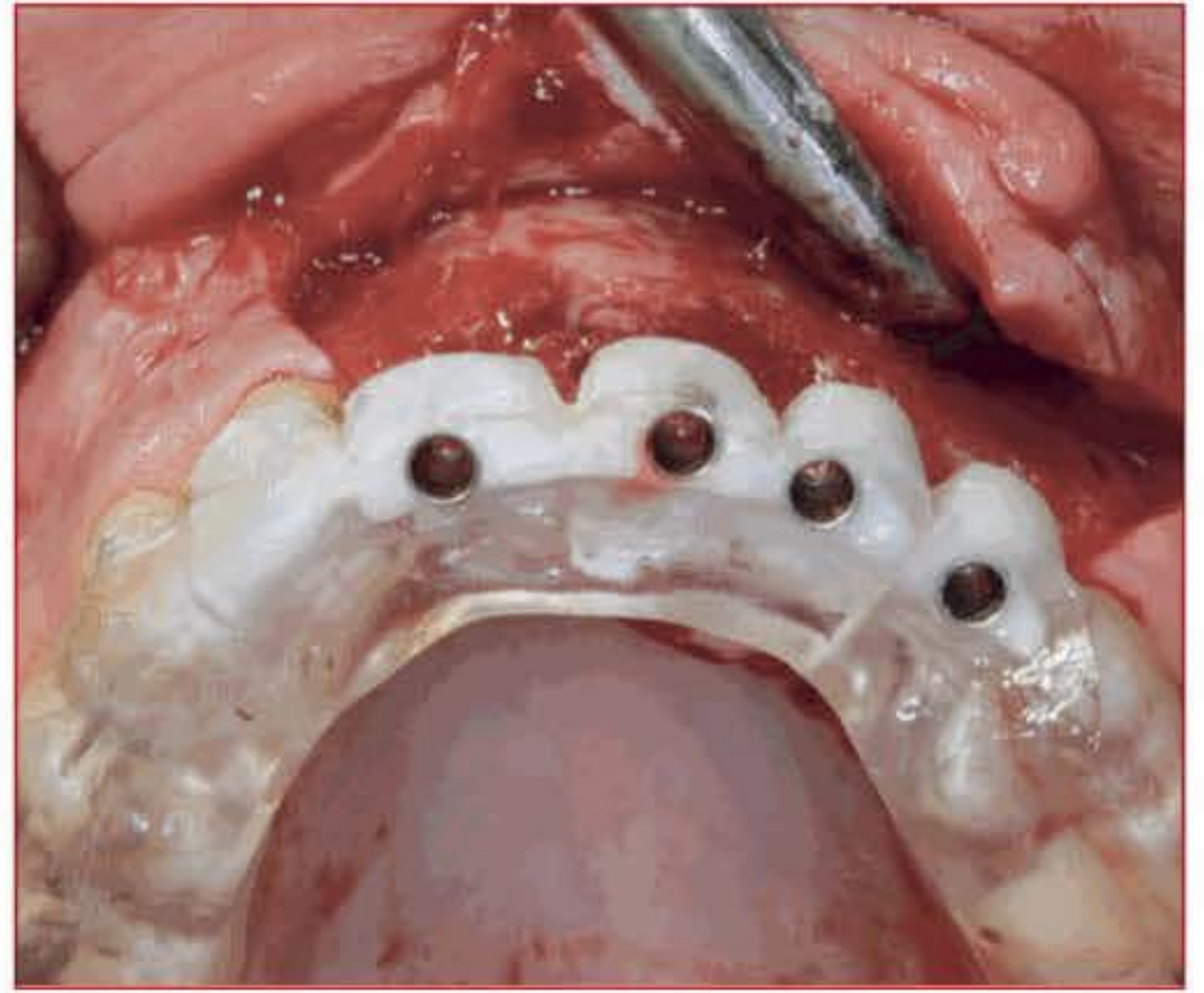


Fig 14-60 Placement of the implant template after removal of the osteosynthesis material, with check of stable positioning.

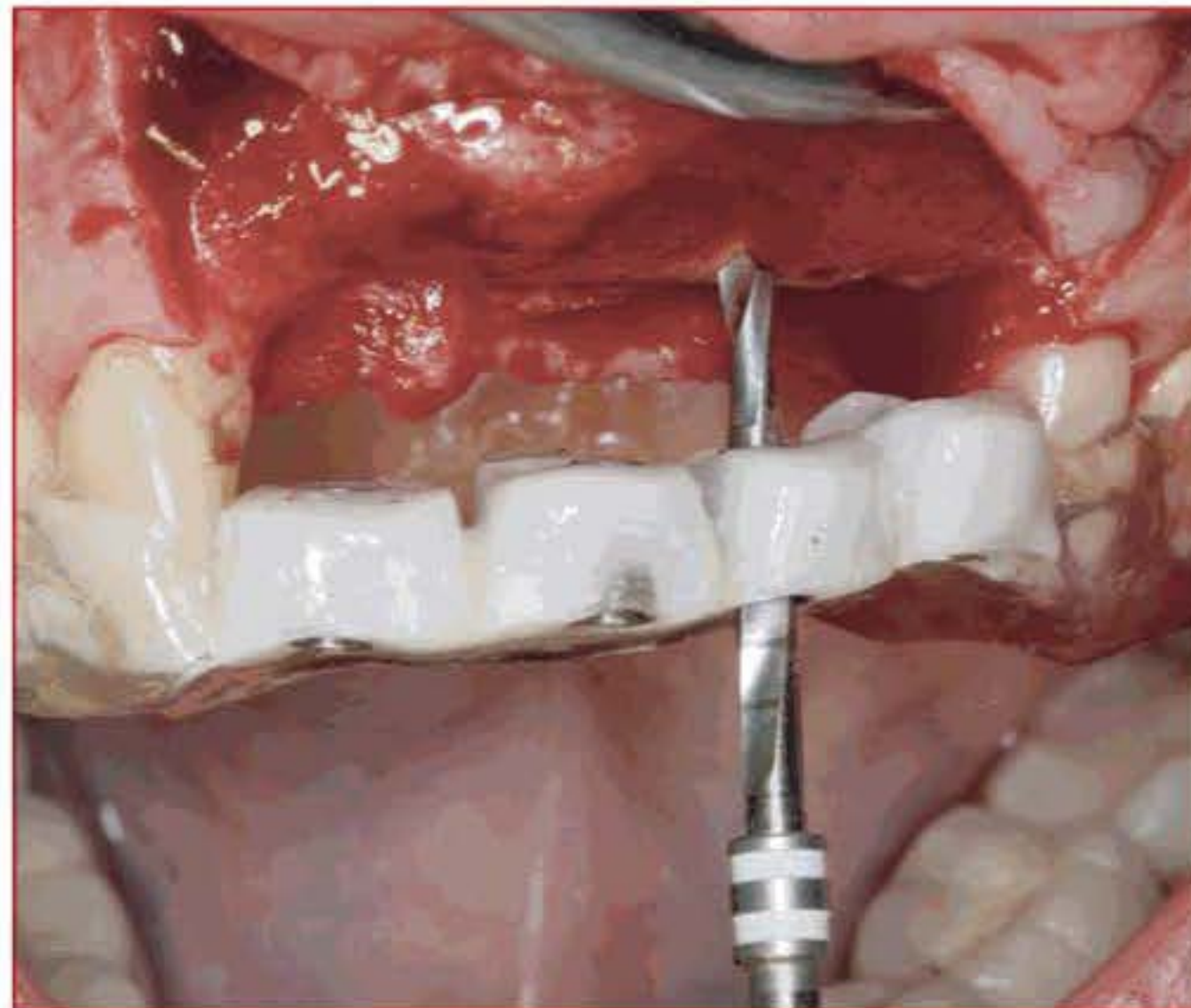


Fig 14-61 Preparation of the cavity in accordance with the CBVI-based implant plan. The distance between the bottom of the drilling template and the crestal alveolar ridge is clearly visible.

The GALILEOS system offers an integrated diagnosis and planning software in which segmentation is no longer needed.¹⁴ Thus, implant planning can directly follow the examination and can be done in the presence of the patient during the consultation. This procedure considerably facilitates patient communication. No further interfaces are necessary in the continued process. After the planning is completed, it is digitally archived and sent to the manufacturer so that the template can be produced. Use of the 3D template allows the plan to be precisely implemented with a preparation of dental prosthetics, especially for immediate loading. Additional CAD/CAM-fabricated tooth replacement options are also available.

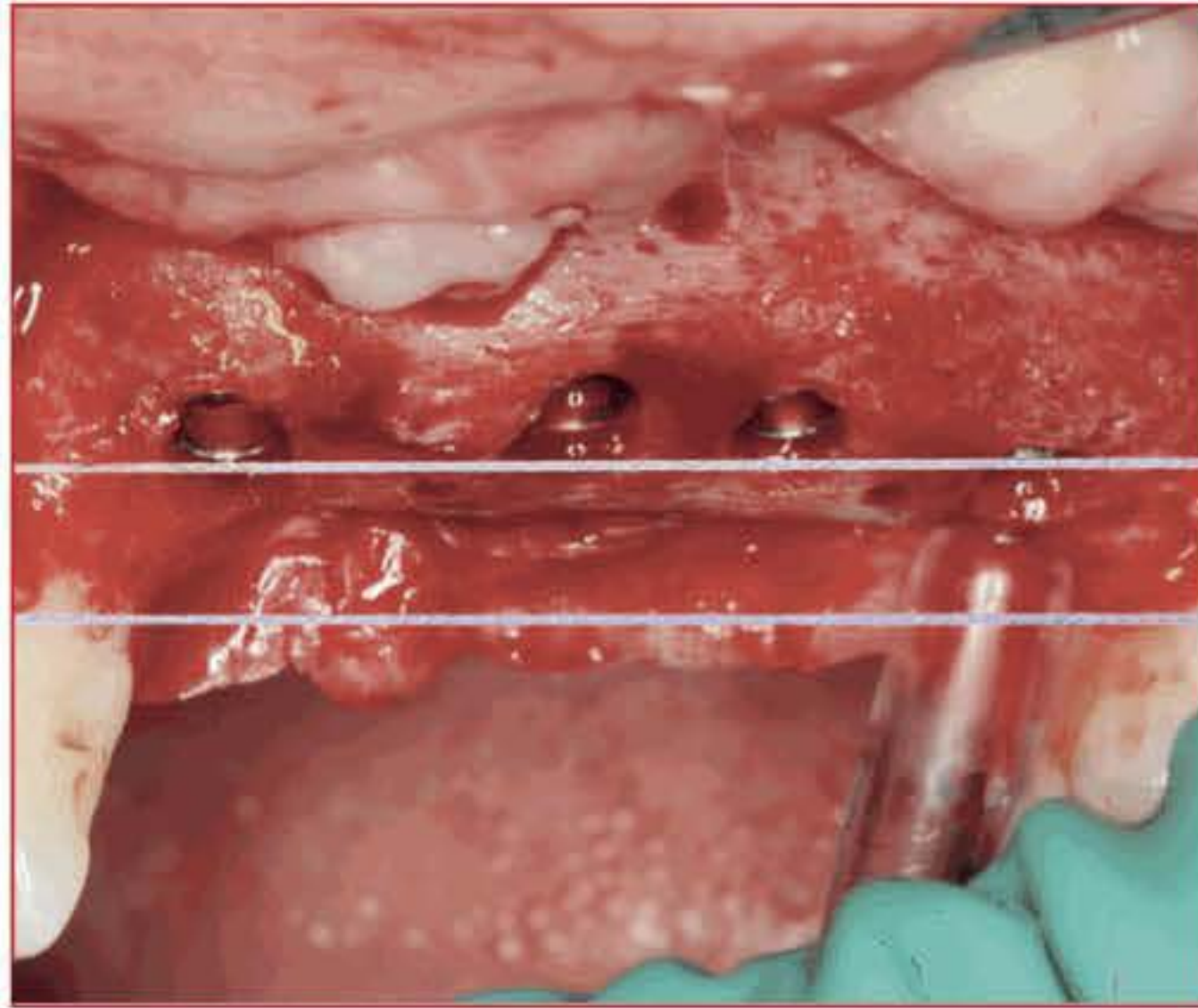


Fig 14-62 Examination of the vertical implant position using the height of the enamel-cement interface of the adjacent teeth with two threads 3 mm apart

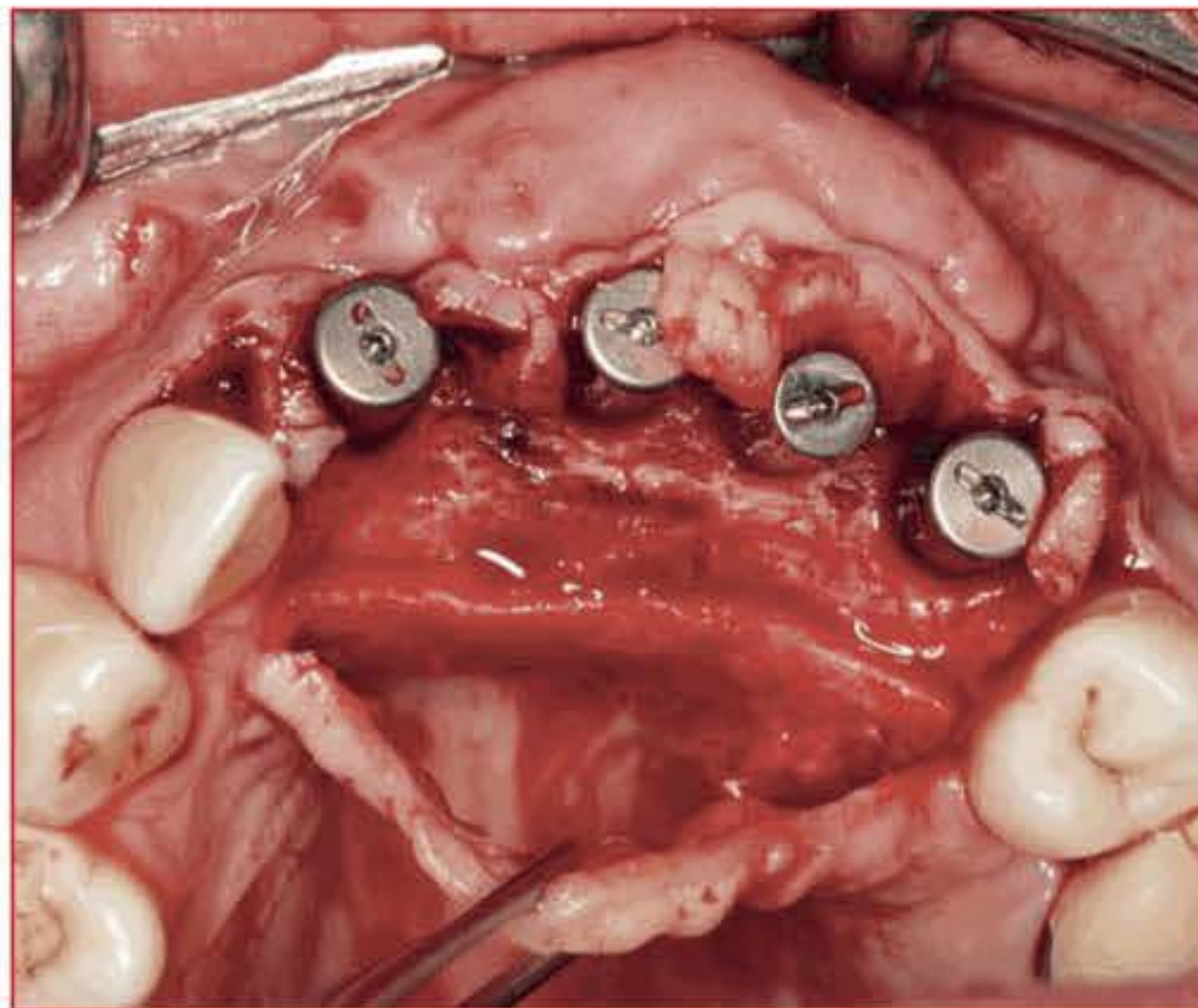


Fig 14-63 Soft tissue plasty at the time of the implant reopening, with palatal bridge flap to contour the peri-implant soft tissue.

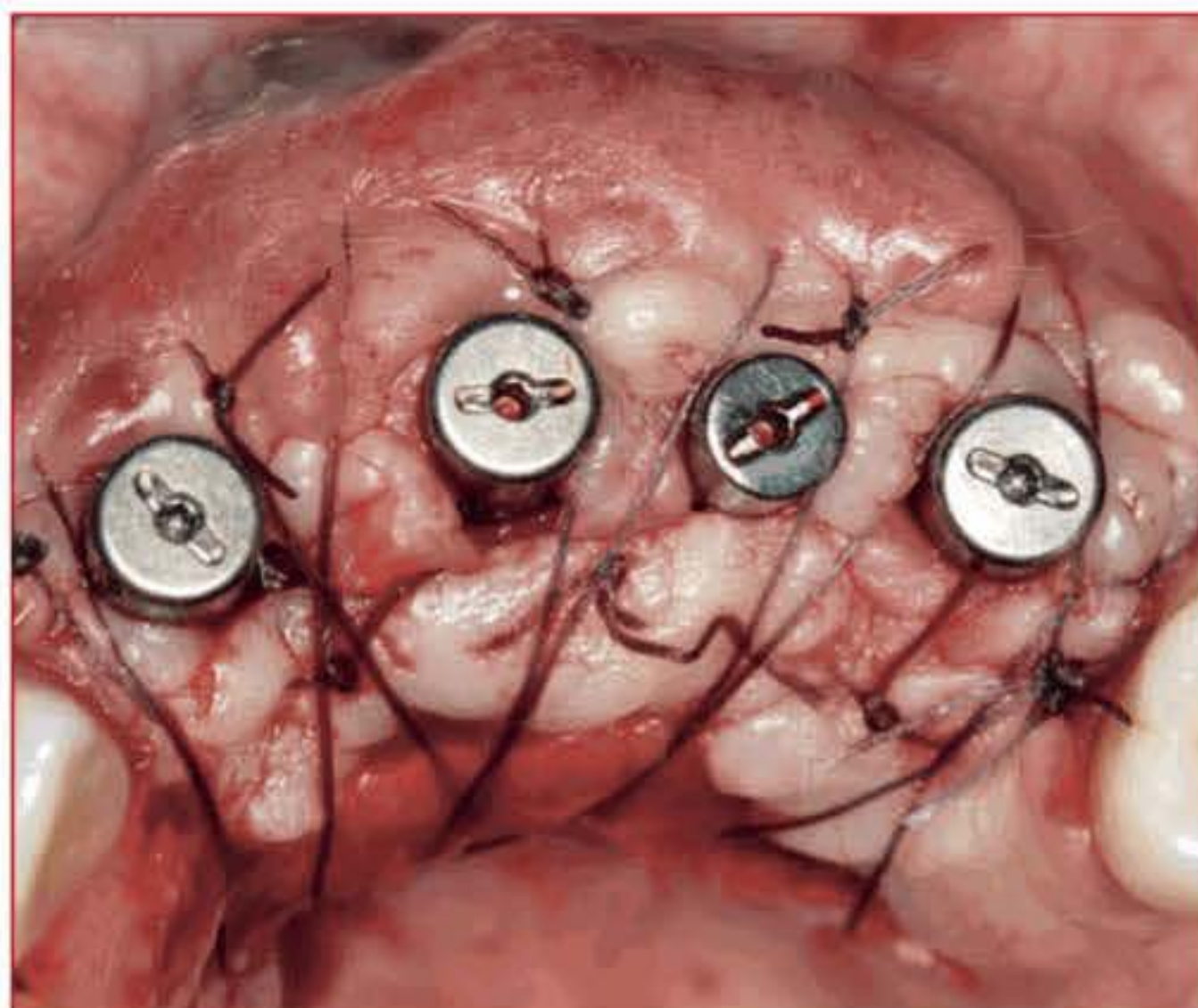


Fig 14-64 Postoperative situation after the second-stage surgery, with placing of keratinized mucosa around the implants.

Fig 14-65 Placement of the implant suprastructures when supplying the definitive prosthetic appliance. Owing to the length of crowns 11 to 21, castable crown suprastructures were individually shaped.



Fig 14-66 Clinical situation 4 weeks after incorporation, with recontouring of the peri-implantal mucosa appropriate for this stage.



Fig 14-67 Smile line after definitive prosthetic accommodations and mobilization of the upper lip using vestibuloplasty.



14.4.1 Postoperative Assessment

After implantation, 3D imaging is also suitable for postoperative assessments. The position of the implants can be represented in 3D and any incorrectly positioned implants can be immediately identified. Clinically noticeable findings can be clearly evaluated in this way (Figure 14-68).

Furthermore, osseointegration of the implant can be evaluated and any bone loss can be accurately determined. In addition to the clinical examination, this permits any osseous complication to be quantified exactly radiologically (Figure 14-69). Even rare complications such as retrograde peri-implantitis can be diagnosed using 3D imaging.

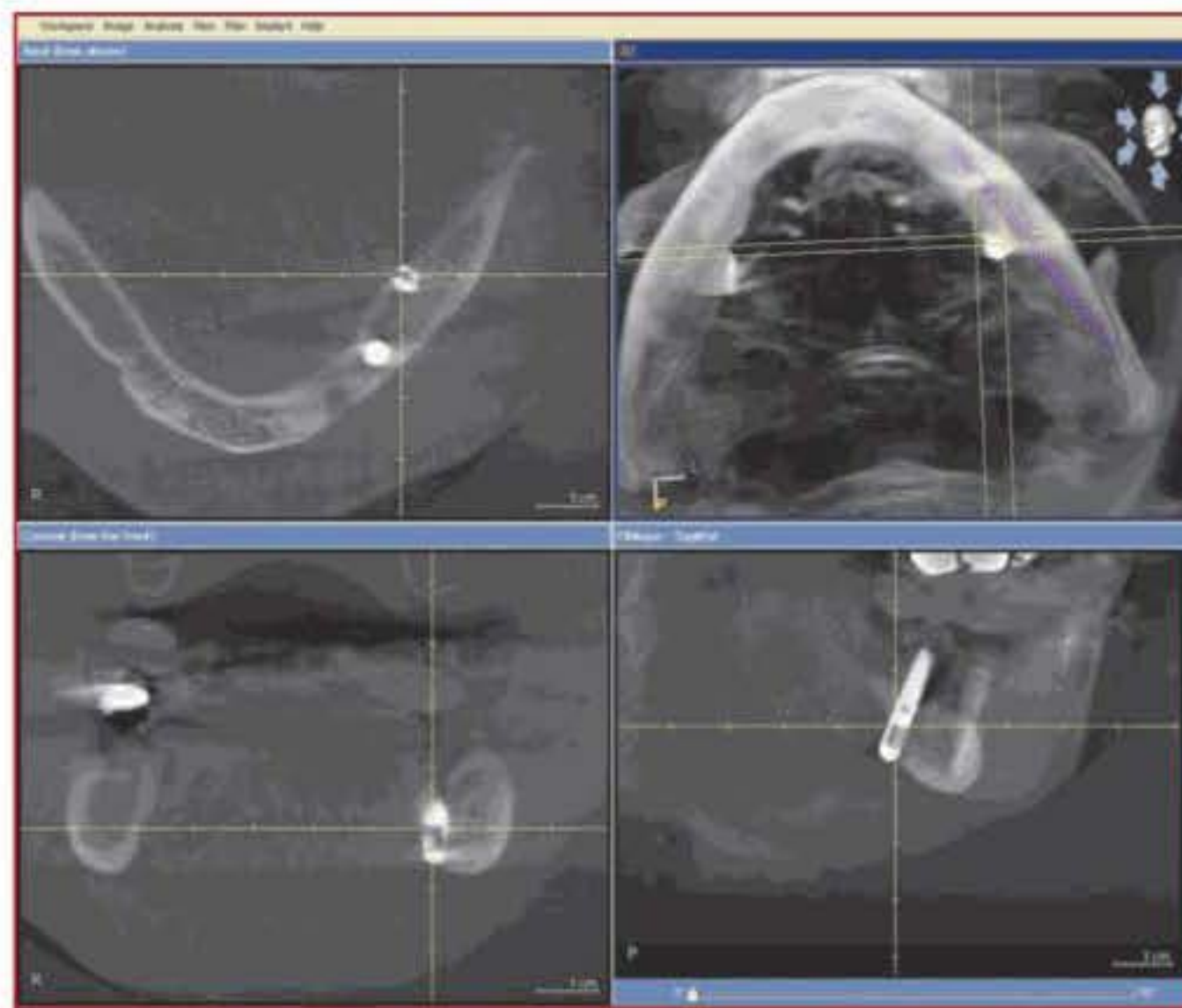


Fig 14-68 Control image in peri-implant inflammation of implant 37. To avoid a nerve lateralization, a paraneural implant position was selected, which led to a perforation of the implant.

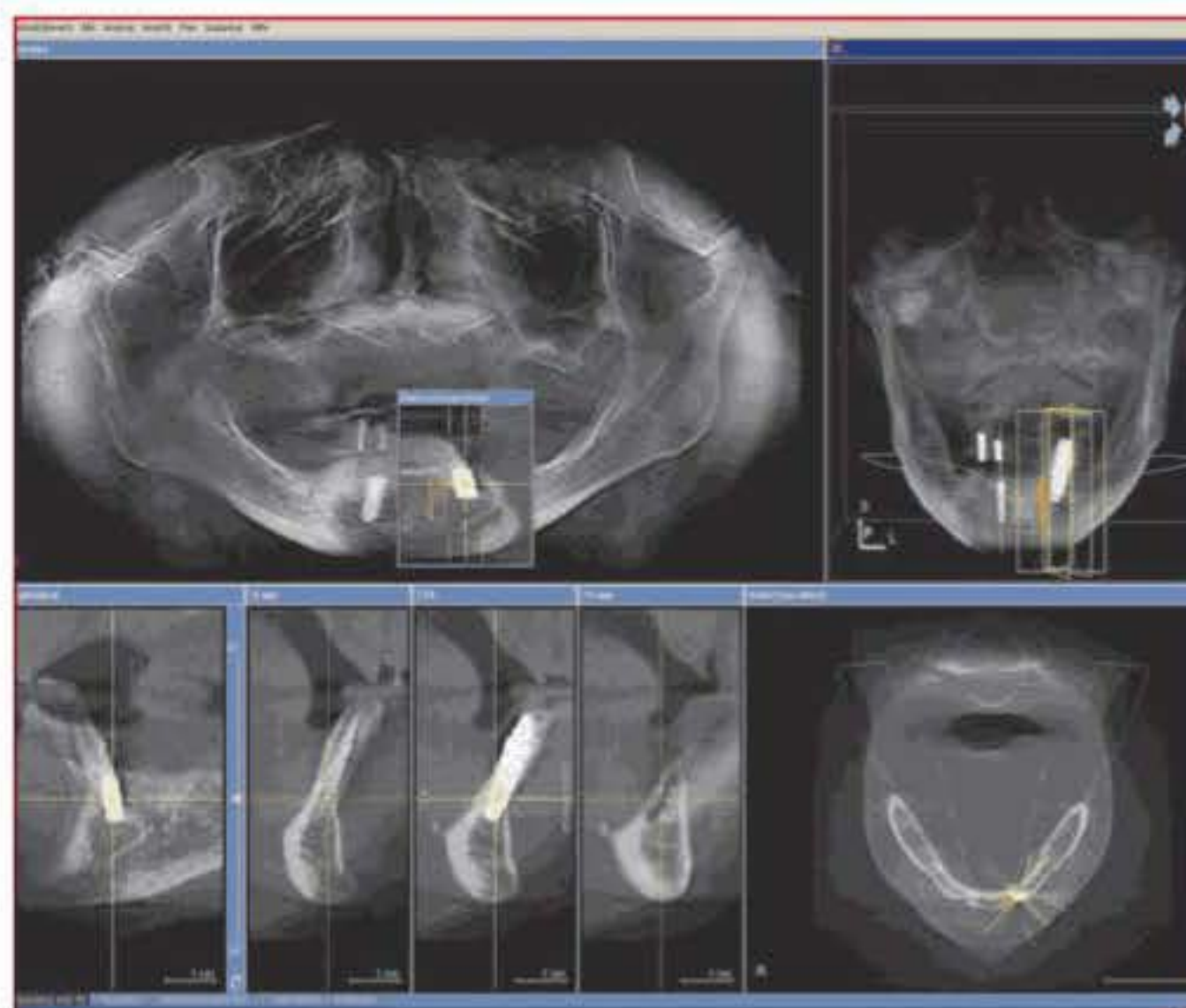


Fig 14-69 Implant insertion in region 34 with inadequate bone availability and spontaneous resorption of the thin cortical bone. Secondary implantation in regions 33 and 43 with reduced-diameter implants and explantation of the unsustainable implant 34.



Fig 14-70 Overlay of a postoperative control image with the preoperatively generated GALILEOS implant plan. Registration is carried out based on markers. Only slight deviations are revealed, mainly in region 17.



Fig 14-71 Overlay of the implant plan in the planning view with check of the implant positioning relative to the sinus lift performed.

Through appropriate easy-to-use software tools, simple procedural controls can be carried out, and the evaluation of the long-term success of an implant therapy can be documented.

However, the disadvantage of 3D imaging in all cone-beam devices is the display of circular metal artifacts around the implant. In response, some manufacturers already offer corresponding metal artifact reduction algorithms to improve image quality.

To examine the precision achieved in the implementation of the virtual implant plan via CAD/CAM surgical guides, one can exactly overlay the preoperative virtual plan with the actual postoperative result. The implementation precision can be examined either by using special registration algorithms with the aid of anatomical features or via a marker-based registration (Figures 14-70 and 14-71).

14.5 Treatment of Complications

14.5.1 Nerve Damage

If the implant plan is insufficient or its implementation is inadequate, damage can occur to anatomical structures during implant insertion (Figures 14-72 to 14-74).¹⁸ Therefore, it is important to determine the exact position of the implants relative to the anatomical structures in the context of further treatment. If there is trauma to the nasal floor or the maxillary sinus, one should first wait and see what happens. Depending on the symptoms that arise, the implants may need to be removed. If a perforation occurs near the nose, the implant tip may be shortened until soft tissue coverage is attained.

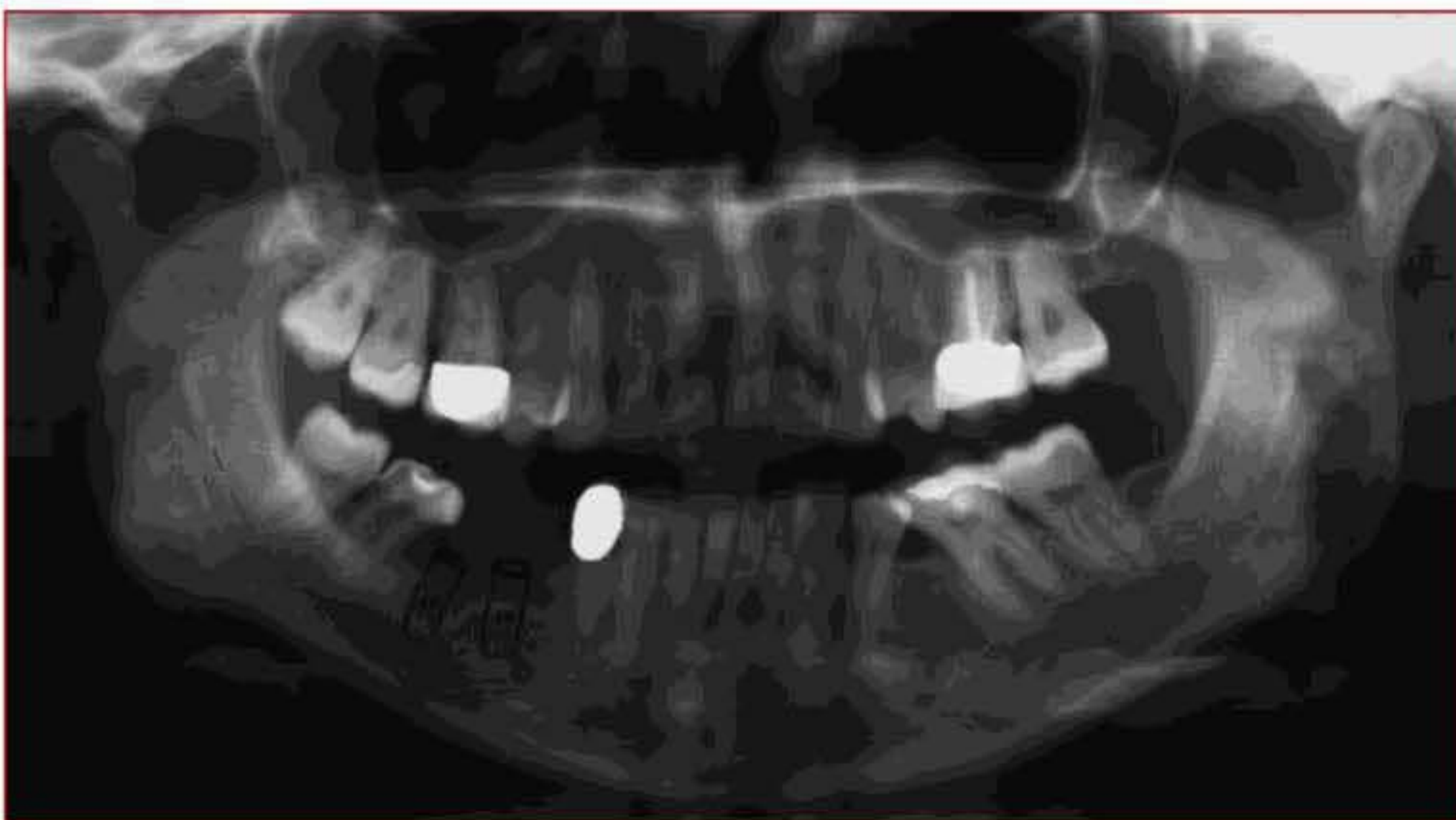


Fig 14-72 Unreferenced implant plan on the right side of the mandible using metric representation of the implants, without calibration elements to verify the enlargement factor.



Fig 14-73 Postoperative control image in persistent anesthesia in the area of the mental nerve. The implant tips overlap the nerve canal.

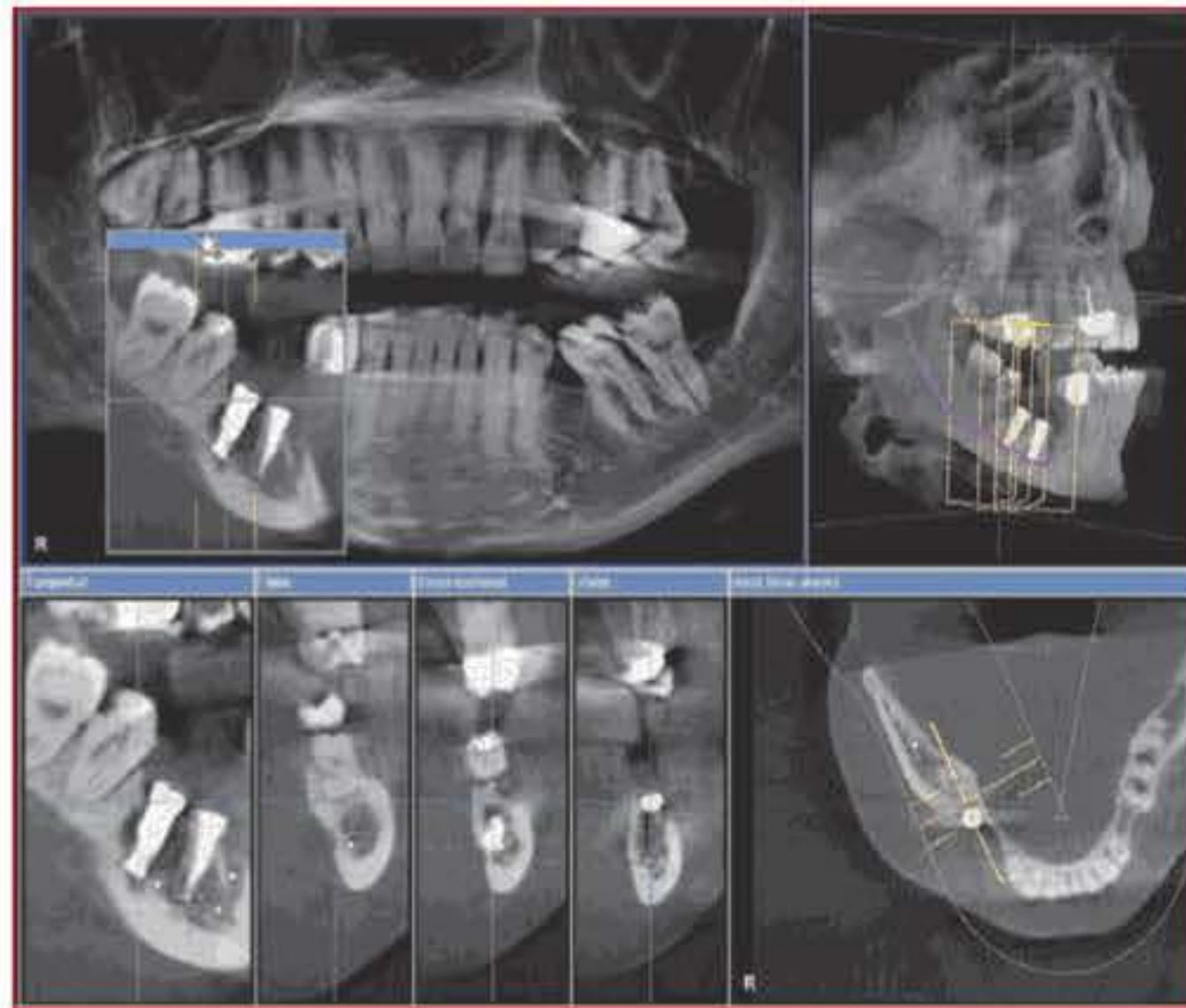


Fig 14-74 Three-dimensional representation of the apical implant positions with direct contact and compression of the inferior alveolar nerve.

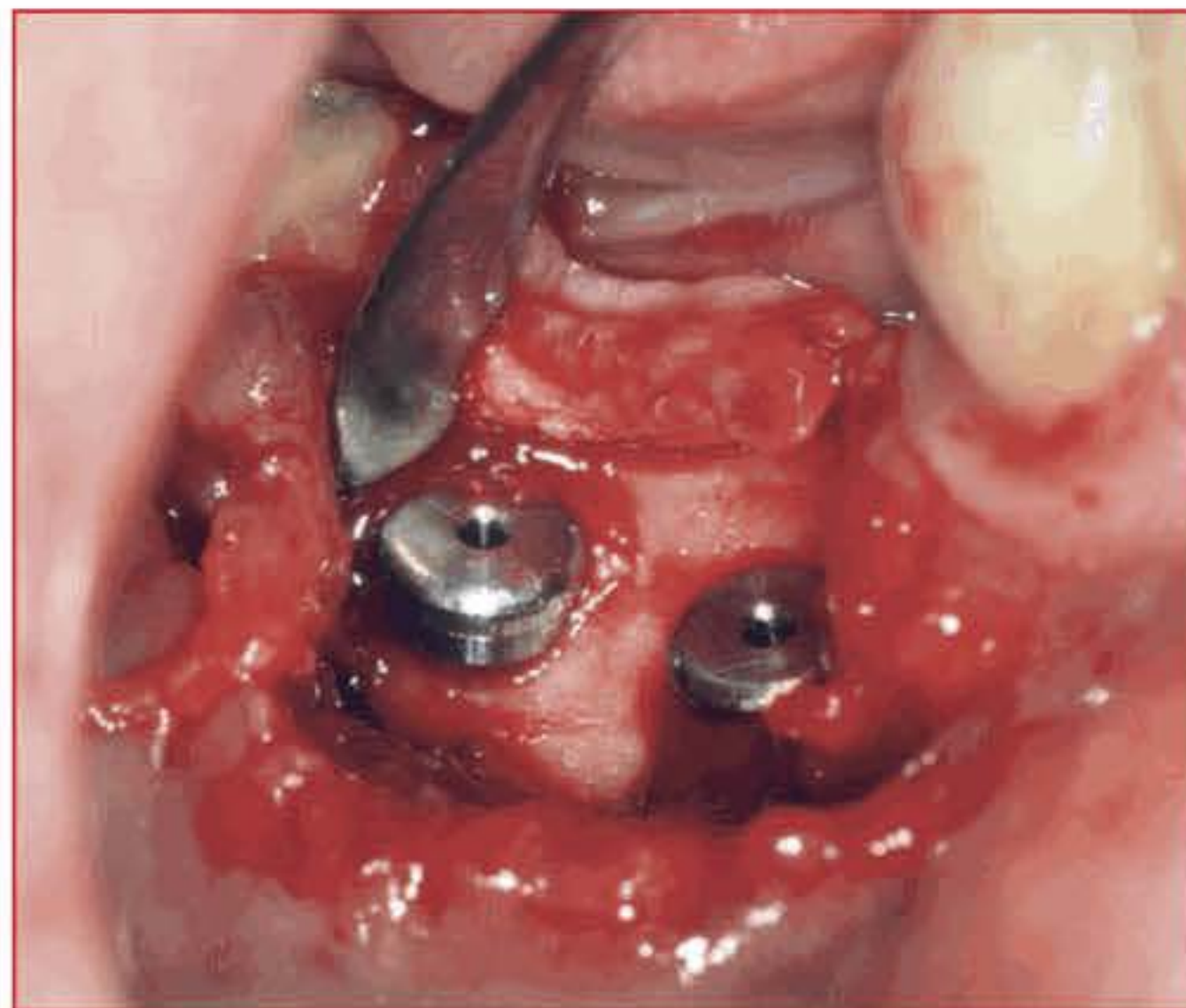


Fig 14-75 Display of the crestal implant position during explantation, with an approximately 2 to 3 mm subcrestal position at the lingual cortical bone.

If the implant is positioned in the direct vicinity of the inferior alveolar nerve and sensitivity is impaired, the implant should be removed from the nerve canal,¹⁹ so that any additional compression of the nerve is eliminated (Figure 14-74). Usually, the implants have to be completely removed in this situation, since the crestal bone availability is not sufficient or the implants sit too far crestally and cannot be prosthetically installed (Figure 14-75).

14.5.2 Unsatisfactorily Positioned Implants

In immediate implantation, the implants may be inserted too far apically and fail to achieve sufficient bone coverage of the implant surface owing to the lack of vestibular lamella. If implants are inserted when the vertical growth of the alveolar process is incomplete, growth is delayed by the osseointegration. The implant then sits too far apically and a very long crown is exhibited clinically. Further therapy decisions are determined by both the spatial situation and the strength of the available vestibular bone (Figures 14-76 to 14-78).



Fig 14-76 Clinical examination with difficult-to-clean implant crown and extremely long soft tissue collar made of pink acrylic resin.



Fig 14-77 Determination of peri-implant bone structures in planned segment osteotomy in the implant planning window. In addition to the position being too far apical, the significant axis tilt is prominent.

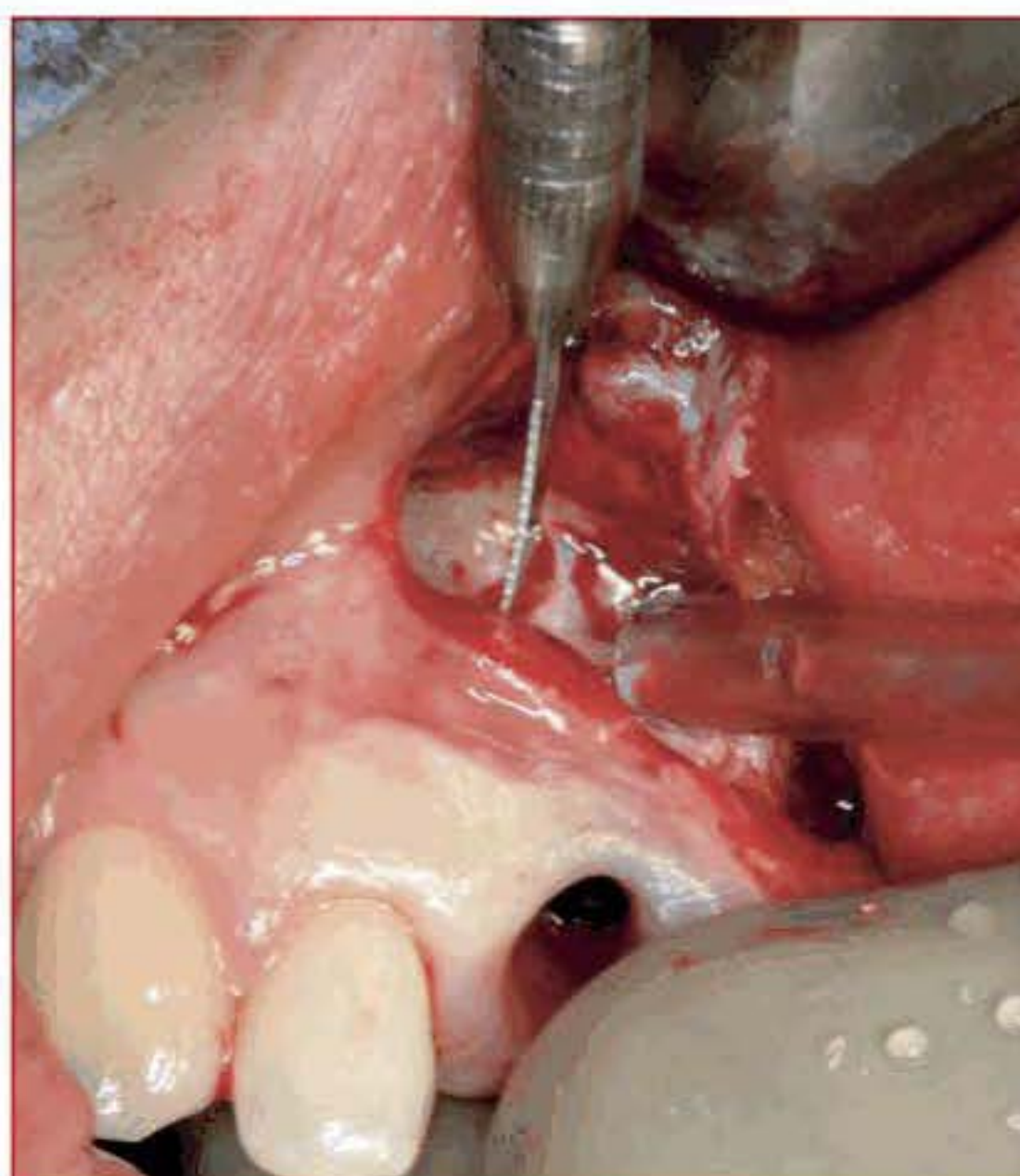


Fig 14-78 Peri-implant segment osteotomy to mobilize the fully osseointegrated implant, which has been inserted too far apically.

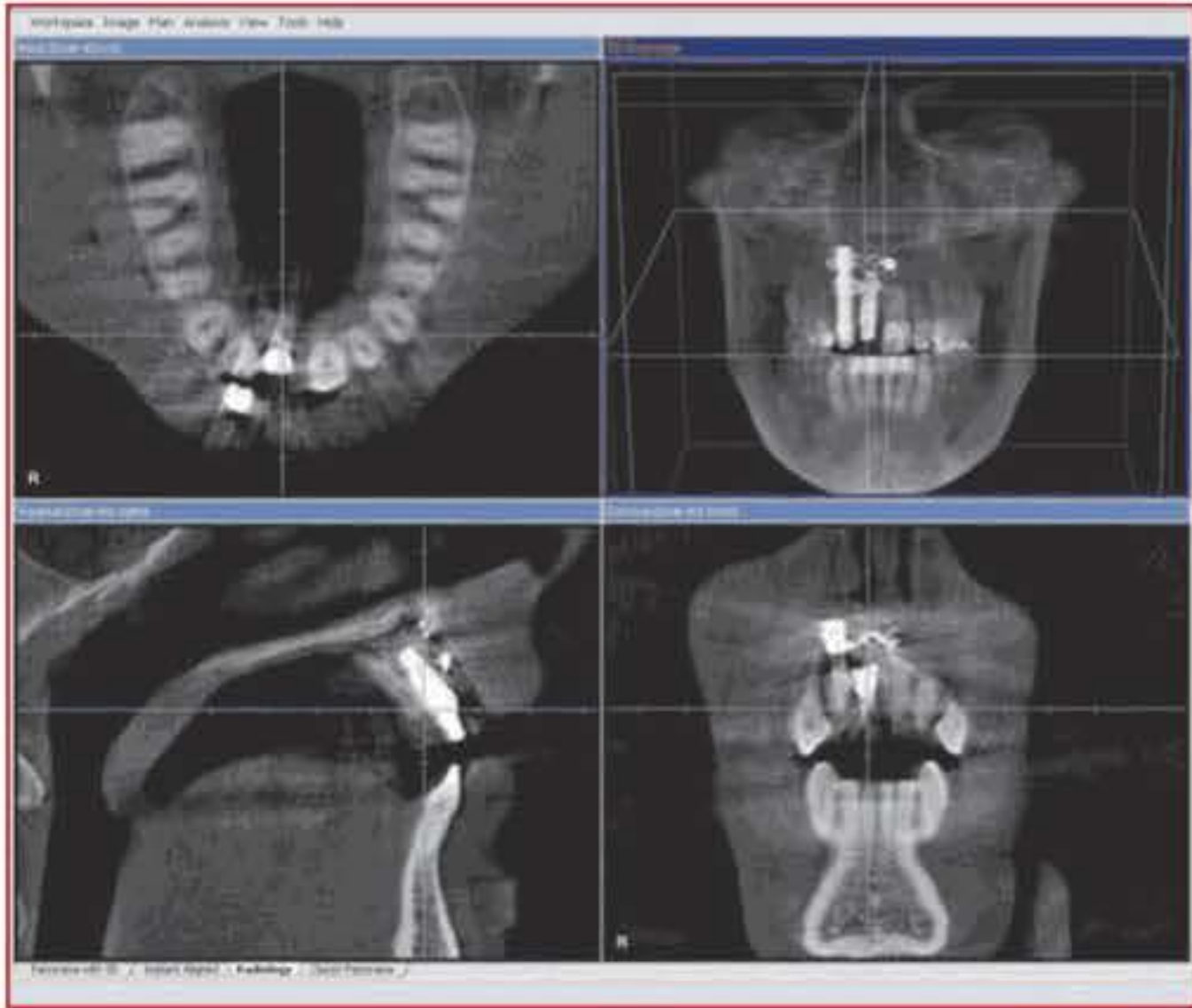


Fig 14-79 Postoperative segment control to examine the integrity of the adjacent anatomical structures.

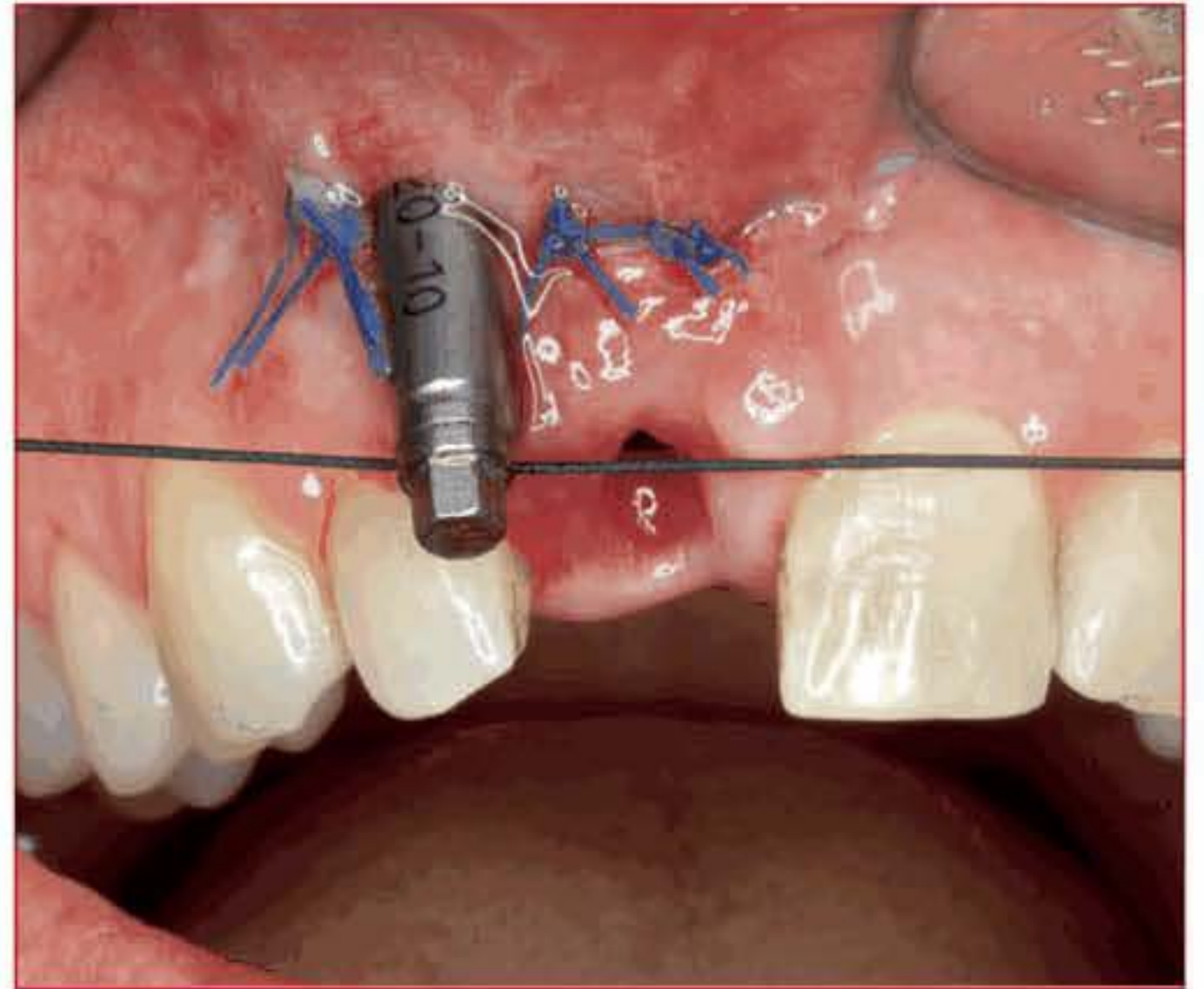


Fig 14-80 Examination of distraction height using the peri-implant soft tissue and the crown contour of the adjacent teeth.



Fig 14-81 Stabilization of the distractor after reaching optimal implant position during the consolidation phase of the distraction.

In cases where there is stable vestibular implant-to-bone contact and sufficient distance to the adjacent teeth and nasal floor, the implants may be shifted to the prosthetically correct position using segment osteotomy. If a position is incorrect by less than 4 mm, this can be done in a one-step distraction.²⁰ If there are greater positional errors, the implant position is corrected using a distraction device (Figures 14-79 to 14-82).



Fig 14-82 Final situation after incorporation of new crown.

14.6 Benefits of Three-dimensional Diagnostics in Implantology

The use of CBVI provides oral implantology with a procedure providing true-to-detail 3D diagnostics for the entire treatment process. During implant planning, the need for augmentative procedures can be precisely determined based on 3D imaging.²¹ The selection of the suitable augmentative process can be discussed with the patient, and the most acceptable method can be selected for each particular situation. The prosthetically oriented plan can be precisely implemented surgically with the computer-aided implant templates. The surgical guide provides the practitioner with a tailored procedure and shortens the operation time. Furthermore, preoperatively fabricated immediate load implant devices are only possible with such a precise plan. Postoperative checks evaluate the operational result, and the cause of any discomfort can be determined in detail. This keeps further injury to the patient to a minimum when treating any complications.^{15,18}

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15 Intraoperative Navigation

Robert A. Mischkowski, Max Zinser and Joachim E. Zöller

15.1 Introduction

Since the 1980s, computers have played an important role in the planning and execution of surgery in many disciplines. In particular, they are used with 3D imaging to visualize anatomical and physiological data in a suitable way for human perception. The advantage of a computer-aided procedure is particularly evident when the image data of the patient can be correlated with the actual in vivo conditions during surgery. This is called image-guided surgery.

The goal of interactive, intraoperative use of 3D image data is realized with navigation systems, which are already widely available. These systems allow for the spatial tracking of instruments, the positions of which are aligned in real time with the anatomical data of the patient on one hand, and with a preoperatively established treatment plan on the other. This requires the successful registration (i.e. reproduction of a mathematically describable relationship: a transformation matrix) between the patient anatomy and the imaging when the position of the patient – but not the relevant anatomy – has changed after imaging has taken place. This relationship can be described mathematically based on the identification and association of common features of image anatomy and patient anatomy in the form of landmarks (point-to-point registration) or surface contours (point-to-surface registration). After registration, this relationship must remain constant for the duration of the surgery or at least until the next registration procedure; otherwise, the transformation matrix no longer describes the actual image-object relationship, and the instruments can be superimposed on to incorrect areas of the image. Landmarks are defined as special points that are easily identifiable on the patient and in the image and that are in a fixed relationship to the object of interest: either part of it or tightly attached to it. Natural landmarks are elements of the patient's normal anatomy, such as the anterior nasal spine or the interincisal point. Artificial landmarks generally are geometric objects that are attached to the patient in a fixed and reproducible manner (fiducial markers). During a marker-based registration, the tip of an indicating instrument (pointer) is placed on a patient landmark, thus notifying the system where the actual point is located on the patient. With three such patient-image point pairs, the transformation matrix between the image coordinates and the patient coordinates can be calculated (point-pair matching). In practice, more point pairs – usually five or six – are often used to increase precision. Surface registration is an alternative to marker-based registration. Here, the surface of the object is traversed with either an indicating instrument or a laser pointer. The system creates a spatially oriented virtual surface model using the established point cloud, and this model is matched with the saved image data of the object (surface matching). Then, the transformation matrix of the navigation arrangement is calculated from the spatial position of the matched surface model.

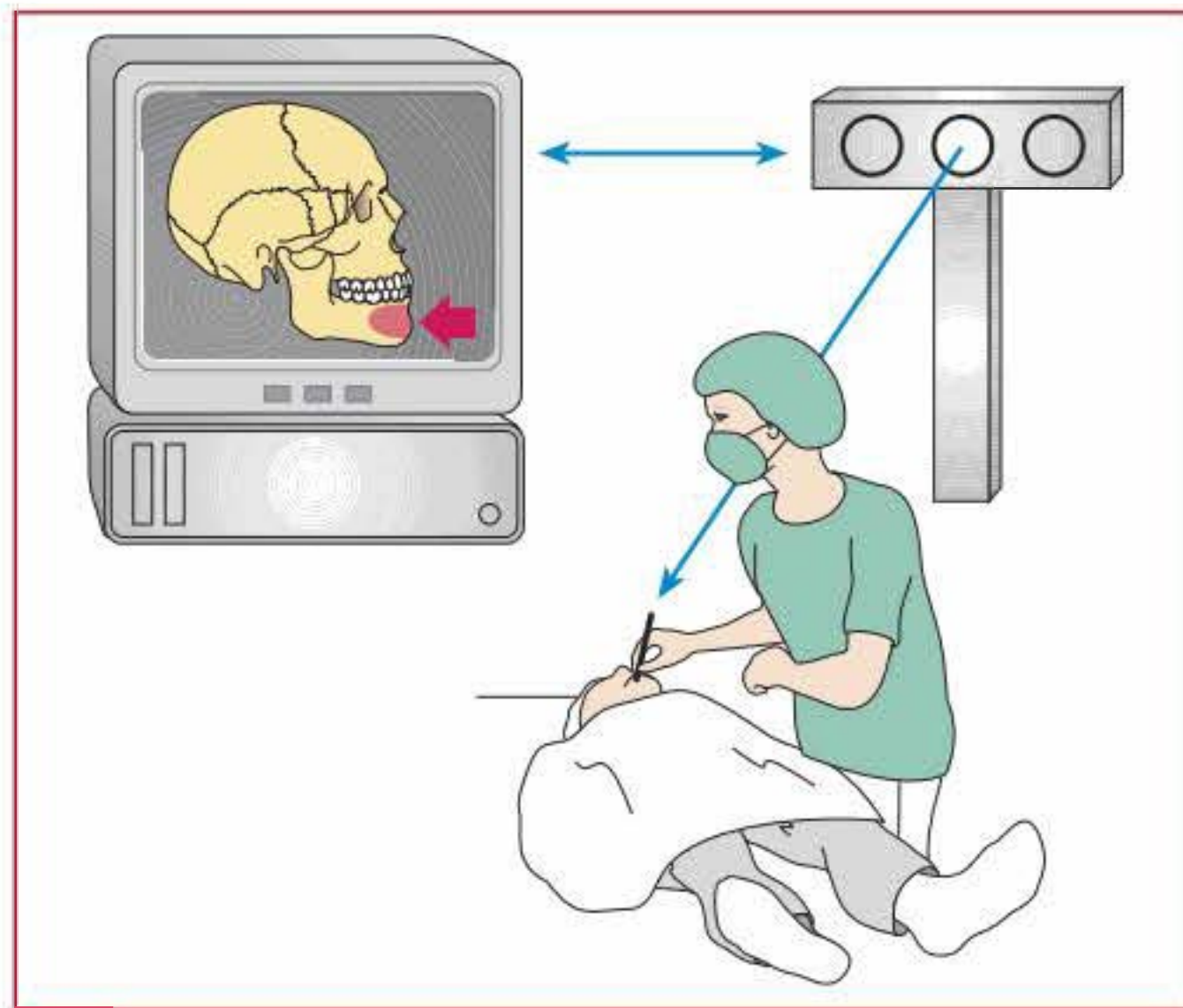


Fig 15-1 Schematic representation of infrared-based intraoperative navigation. The surgical instruments are located using an infrared camera and placed in a spatially correct relationship to the stored image data of the patient.

For the instruments and the object of interest to be localized, they must carry active or passive recognition elements such as ultrasound emitters, reflectors, light-emitting diodes or electromagnetic coils. The navigation device contains a detector unit that receives the emitted signals and forwards them to the connected processor. The spatial position of the recognition elements and the instruments or objects that are in a fixed and known spatial relationship with them is calculated from the phase differences of the incoming signals (Figure 15-1).

The first system for intraoperative navigation was presented in the late 1980s by Schlöndorff and Mösges,^{1,2} who were the first to patent this technology.³ Image-guided surgery methods have proven to be useful in multiple surgical disciplines, in particular in procedures in which operational precision, protection of surrounding anatomical structures and minimally invasive access are significant. Examples include the removal of intracranial tumors in neurosurgery,⁴⁻⁷ the insertion of pedicle screws in spinal surgery, the implantation of knee endoprotheses in orthopedics⁸⁻¹¹ and interventions in the paranasal sinuses and lateral cranial base areas in ear, nose and throat surgery.^{12,13} The complex anatomy of the craniofacial region leads intraoperative navigation to play a significant role in oral and maxillofacial surgery, opening up new perspectives in implantology,^{14,15} orthognathic surgery,^{16,17} traumatology¹⁸⁻²¹ and tumor surgery.^{22,23} Surgery can be pre-planned with great precision using 2D and 3D imaging and this precision can be carried through into the operative procedure. Modern image-guided systems are able to process image data generated via CT, MRI, positron emission tomography (PET), ultrasound and fluoroscopy. The software permits the superimposition of image data from different imaging methods in the correct spatial relationship with one another. This largely automatic feature is called "image fusion"²⁴ and provides the surgeon with a novel combination of anatomical and functional information about a given pathological lesion.²⁵

Fig 15-2 View of the operating unit of the VectorVision navigation system. It consists of an infrared camera (at the support arm, left side) and a computer workstation for data processing in a movable housing. The image data are visualized on the monitor on the right arm of the support.



15.2 Procedures Using Cone-beam Volumetric Imaging

Until now, CT has been the most frequently used modality of 3D imaging for intraoperative navigation in oral and maxillofacial surgery. Since CBVI technology provides diagnostic information about high-contrast structures similar to CT, the use of CBVI data to complement previously established methods for computer-assisted surgeries is an obvious extension of this technology. CBVI has the advantage of exposing the patients to only a fraction of the radiation dosage of conventional CT devices. Furthermore, CBVI images can be acquired much more easily and quickly since the equipment is available locally and is operated by in-office personnel, eliminating appointments and waiting times as well as the problems of data transfer.

Indications for CBVI-supported navigation can include the placement of implants, removal of foreign bodies, removal of pathological lesions in the area of the midfacial skeleton and in the paranasal sinuses, as well as the treatment of traumatic or tumor-related deformities. Navigation in the mandibular region is limited with systems developed primarily for neuronavigation (such as VectorVision,¹³ BrainLAB, Heimstetten) as, generally, these systems do not allow for dynamic referencing of the mobile mandible. However, imaging-guided interventions in the mandibular area are possible using navigation devices designed for implantation, such as the RoboDent device (RoboDent, Berlin).

Patient imaging is carried out using the usual reference markers for image-to-patient registration in that particular system. In the BrainLAB system (Figure 15-2), these markers are radiopaque spheres that are attached in a reproducible position on the head of the patient using a headset or an occlusal splint. The simplest referencing option is to attach the markers to the skin, along with corresponding sockets. When positioning the markers, one should ensure that at least five markers are located within the scan volume and are clearly represented in the images.



Fig 15-3a A 20-year-old female patient with wisdom tooth 18 iatrogenically luxated into the right pterygopalatal fossa. The tooth was removed with the support of the navigation system using CBVI.

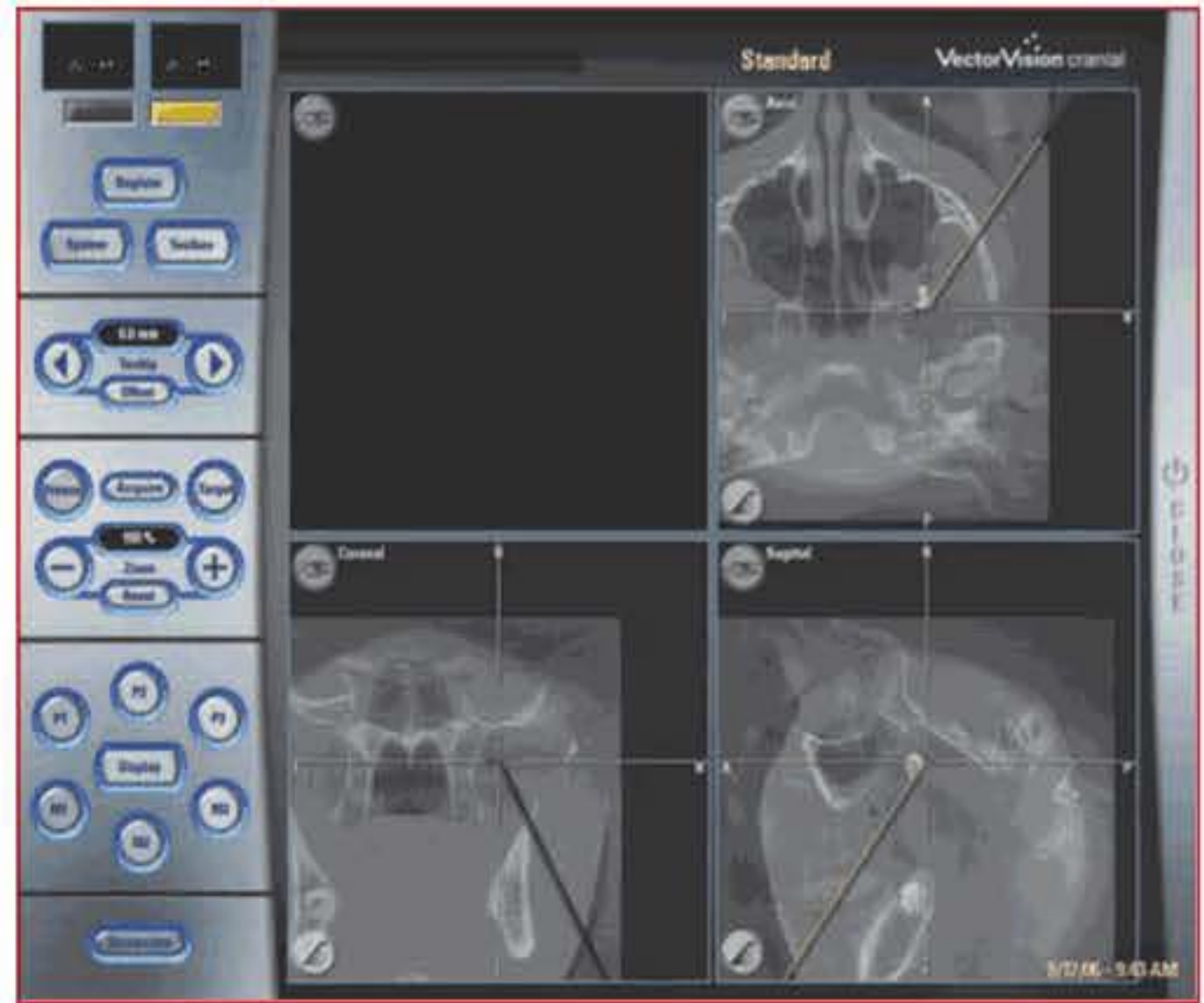


Fig 15-3b The screen of the navigation device shows the targeting of the tooth with the aid of the navigation pointer.

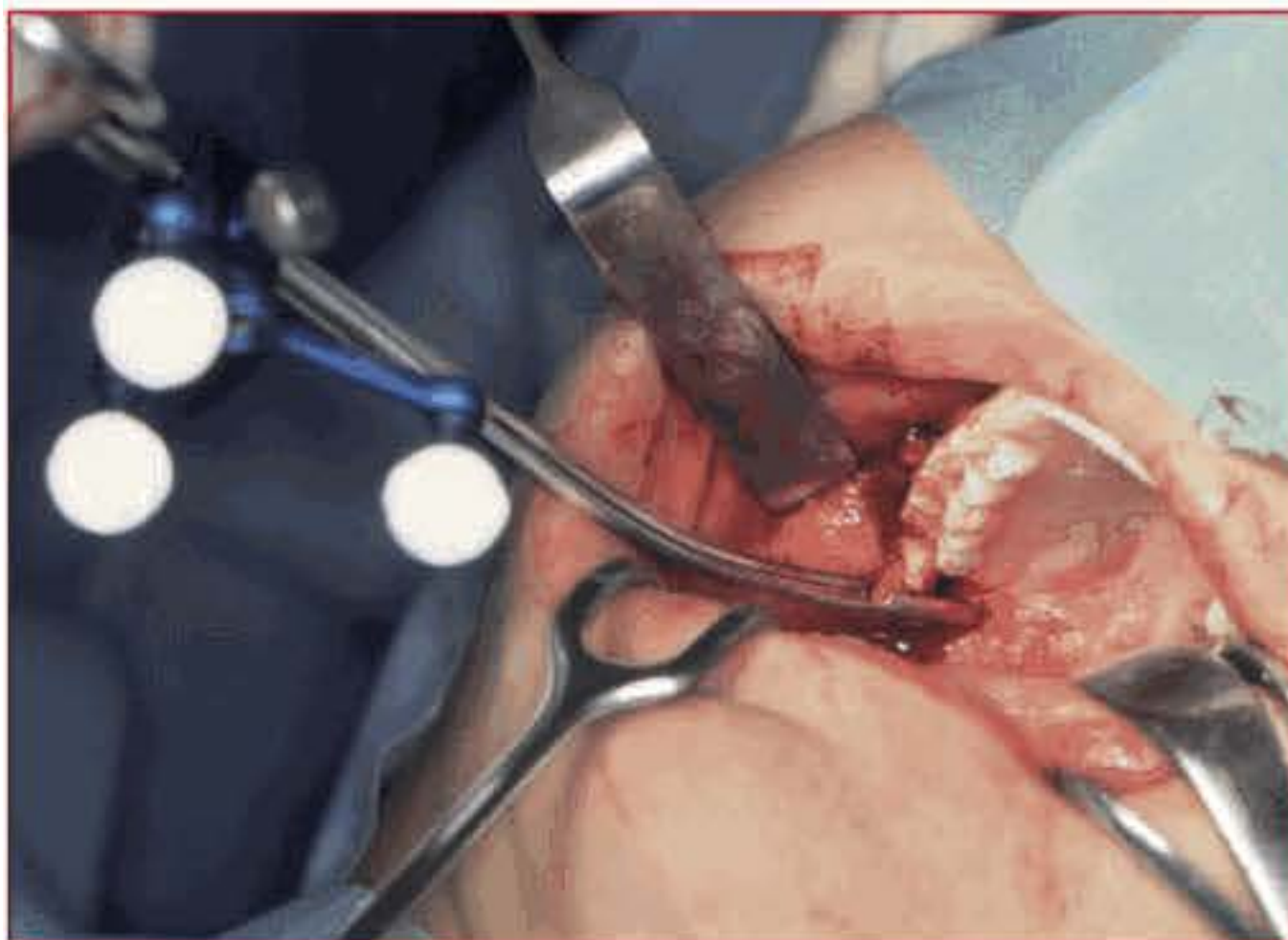


Fig 15-3c The tooth can be easily removed using a referenced clamp, the position of which is continuously provided by the navigation system, without requiring extended surgical exploration of the target area.



Fig 15-3d The removed wisdom tooth.

CBVI image data can be easily exported to the DICOM 3.0 format and read into the planning station of the navigation device. There, they can be processed in the same manner as CT data. Using various planning tools, objects can be segmented, implant positions can be estimated and access trajectories can be determined. In the process, one should remember that the CT values, which are expressed in Hounsfield units, do not apply to the CBVI images; as a result, the thresholds for the rendering of 3D objects have to be manually adjusted. After the completion of the preoperative plan, the data are transferred to the navigation unit as usual. From there on, navigation is performed in the same manner as for CT or MRI data. Figures 15-3 and 15-4 show the use of CBVI-based navigation for foreign body removal and implant insertion, respectively. The procedures used the VectorVision¹³ navigation system with iPlan Cranial 2.5 planning software and VectorVision cranial 7.7 navigation software (software from BrainLAB, Heimstetten).

Fig 15-4a Image-guided implantation in a 58-year-old male with bilateral cleft lip and palate, using CBVI image data. The imaging reflects the difficult anatomical situation resulting from multiple reconstructive operations and bone augmentations.

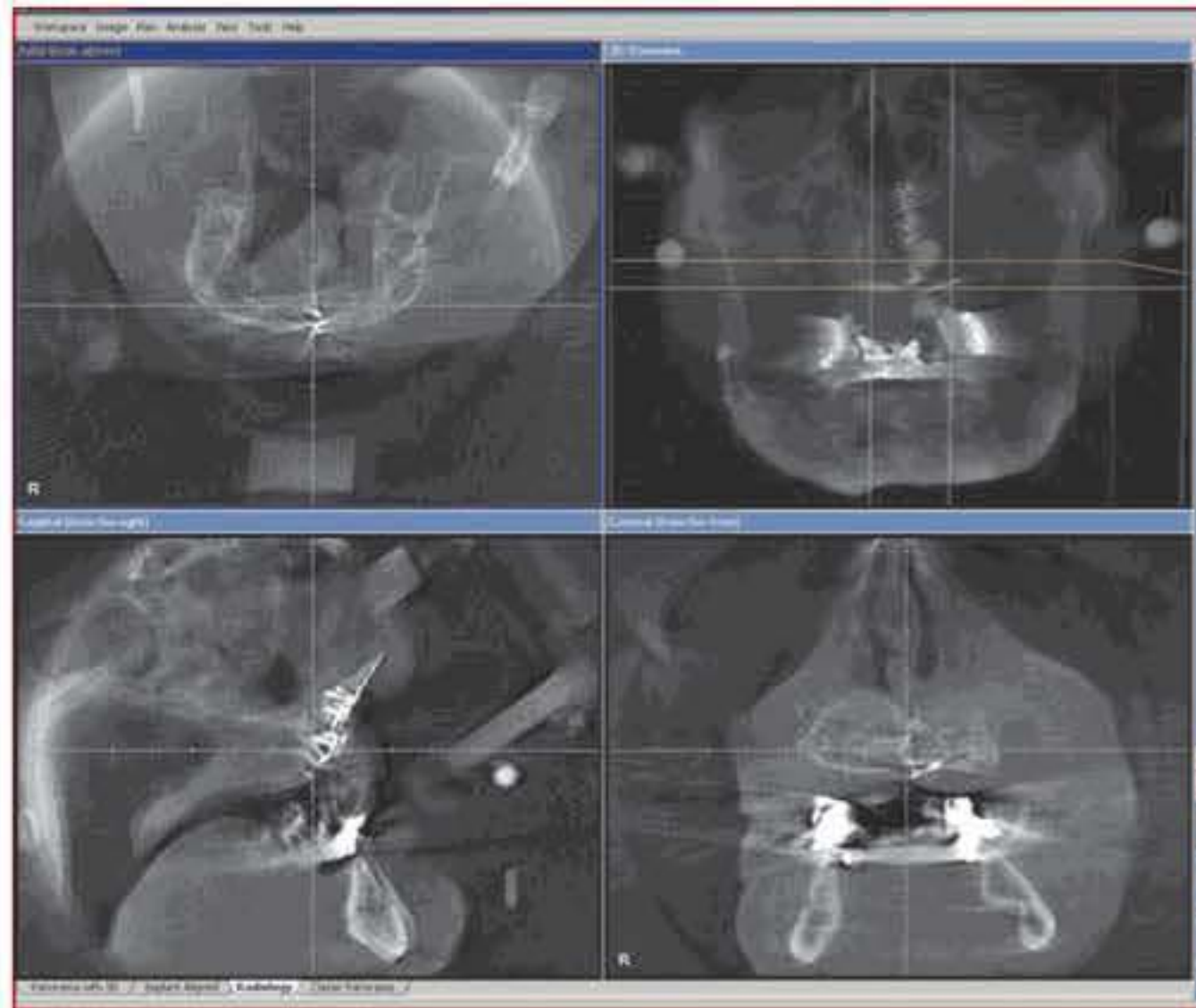


Fig 15-4b The profile of the alveolar ridge does not permit the use of a mucosa-supported drill template.

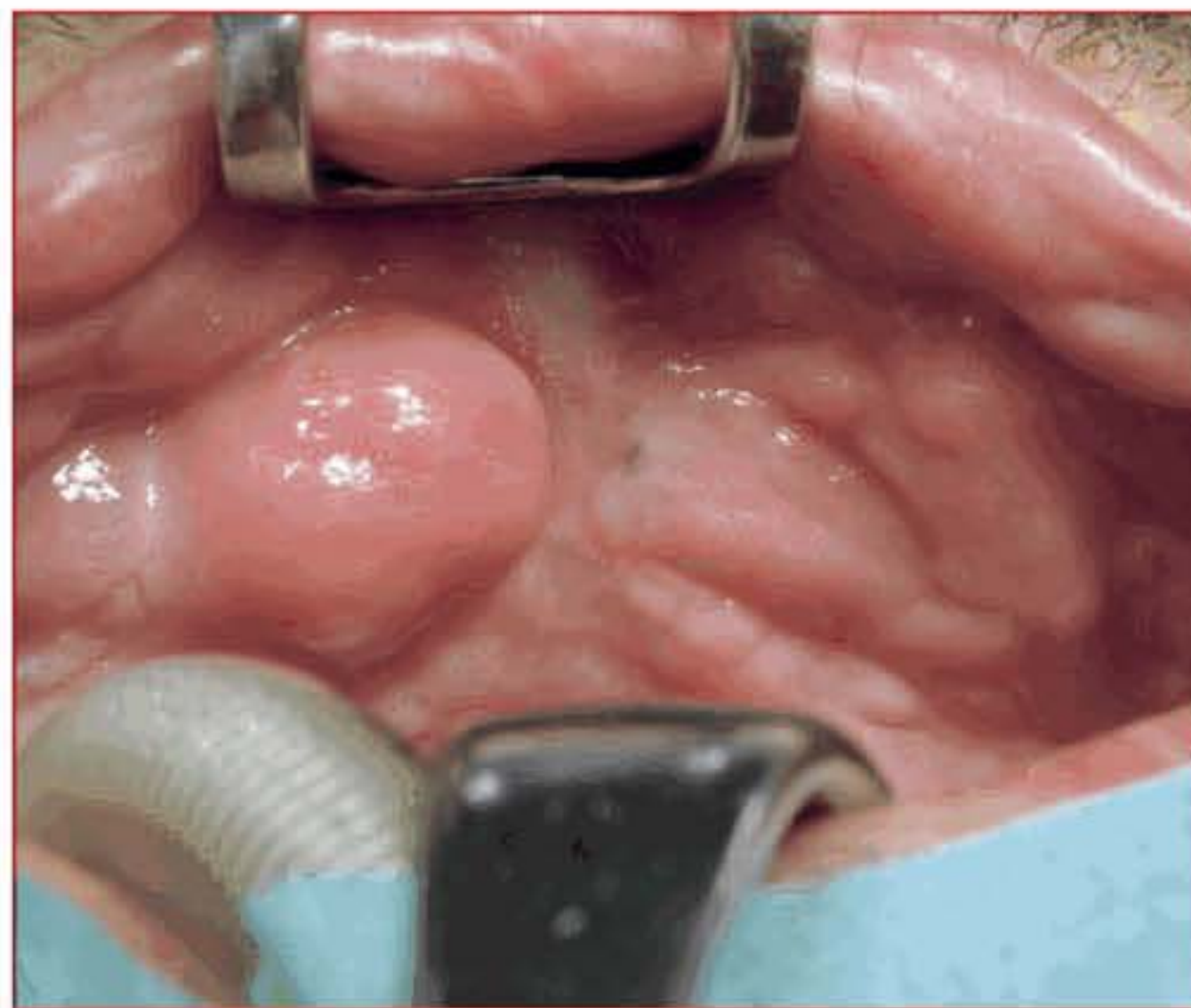
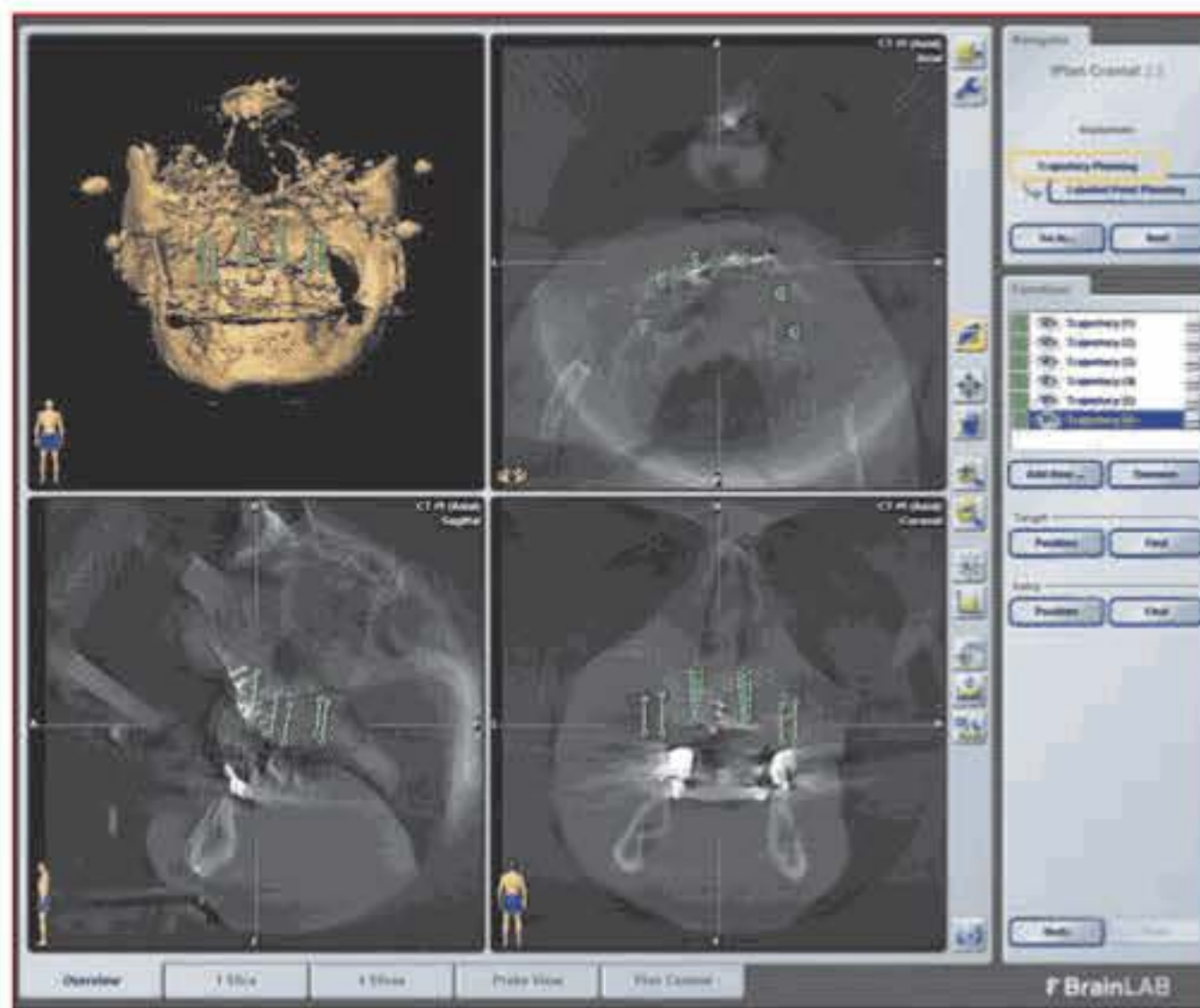


Fig 15-4c Three-dimensional planning of the implant positions.



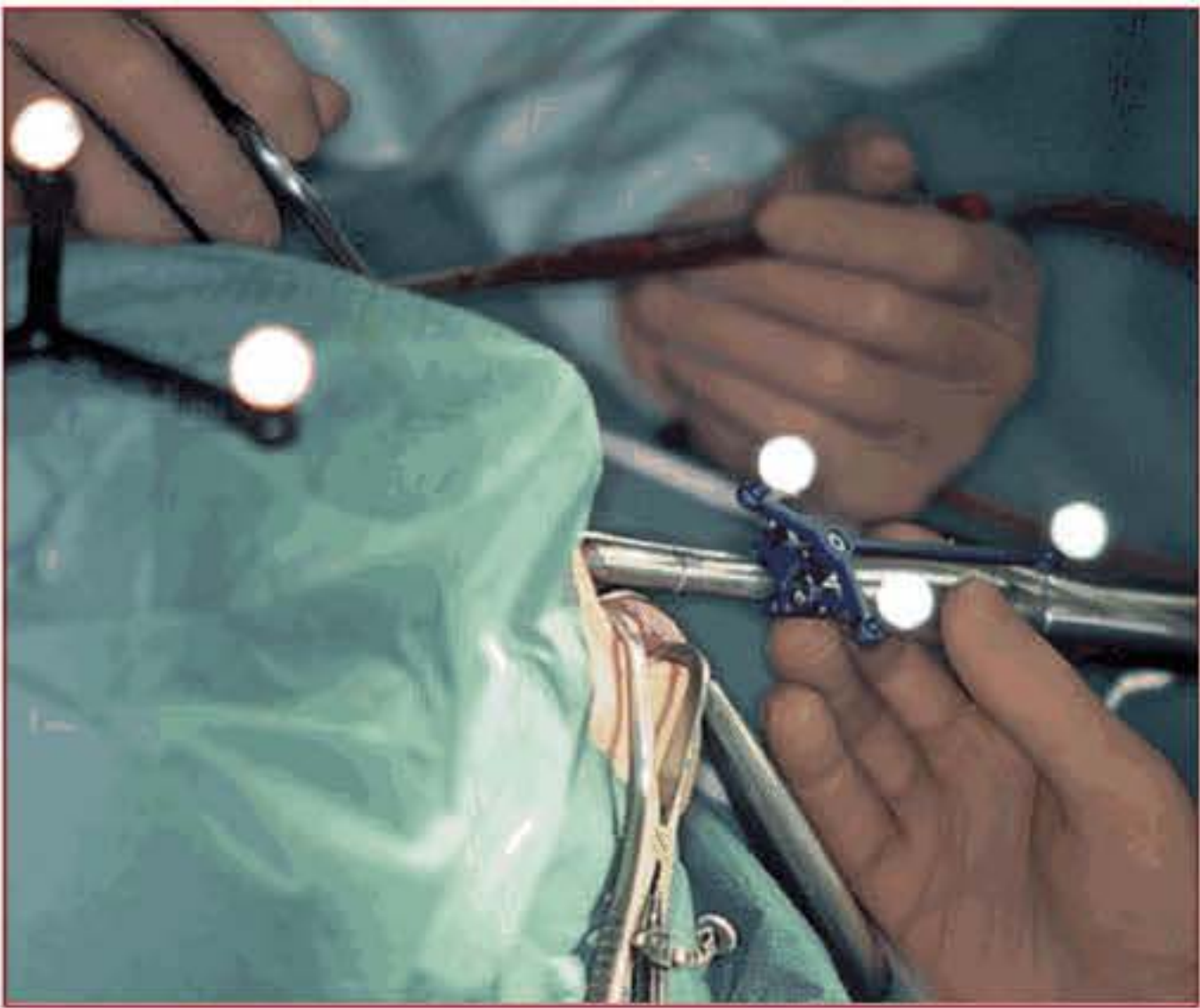


Fig 15-4d *Implant drilling with a referenced hand piece. The position of the drill is displayed on the screen of the navigation system.*

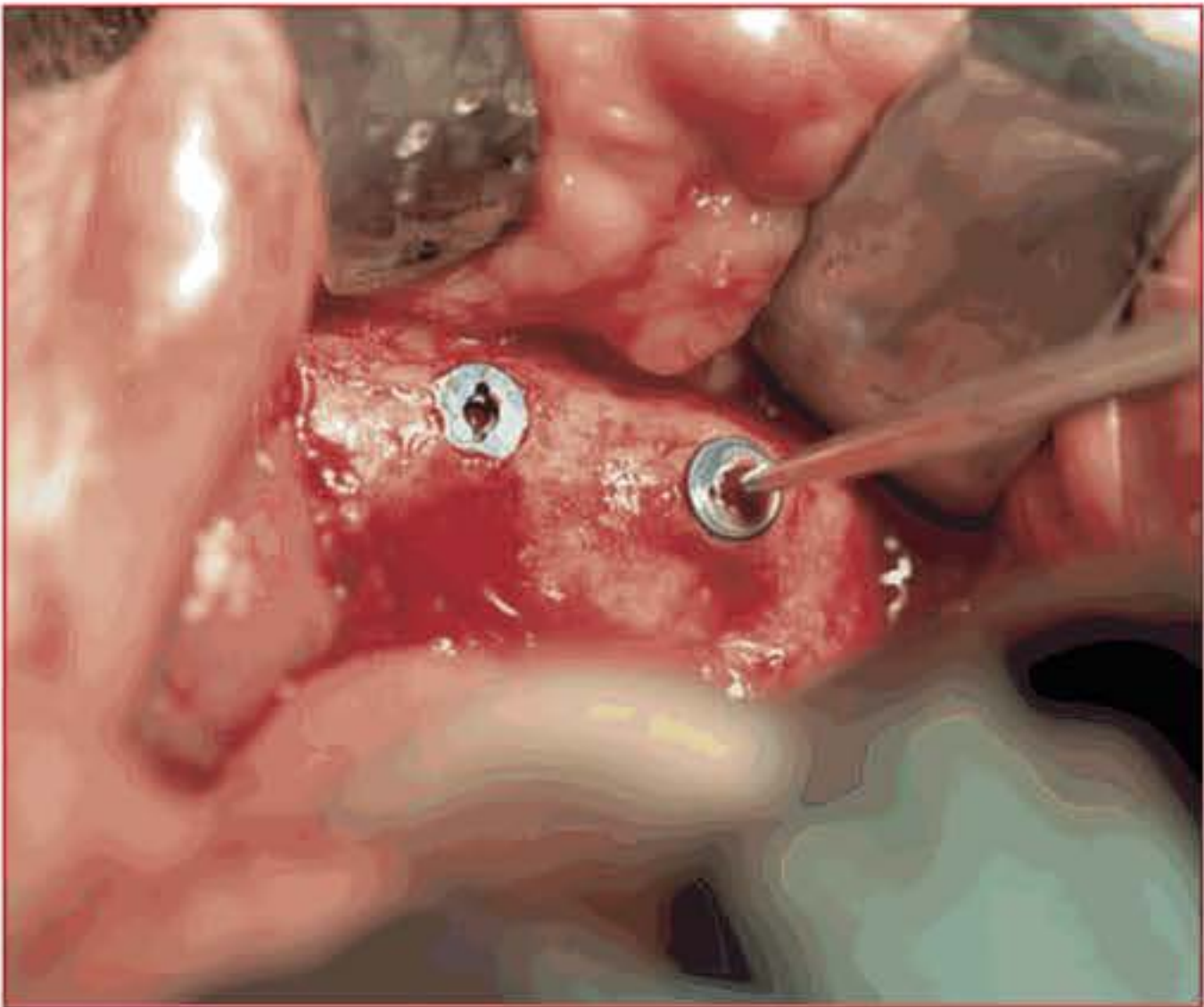


Fig 15-4e *Check of the implant position using the navigation pointer.*

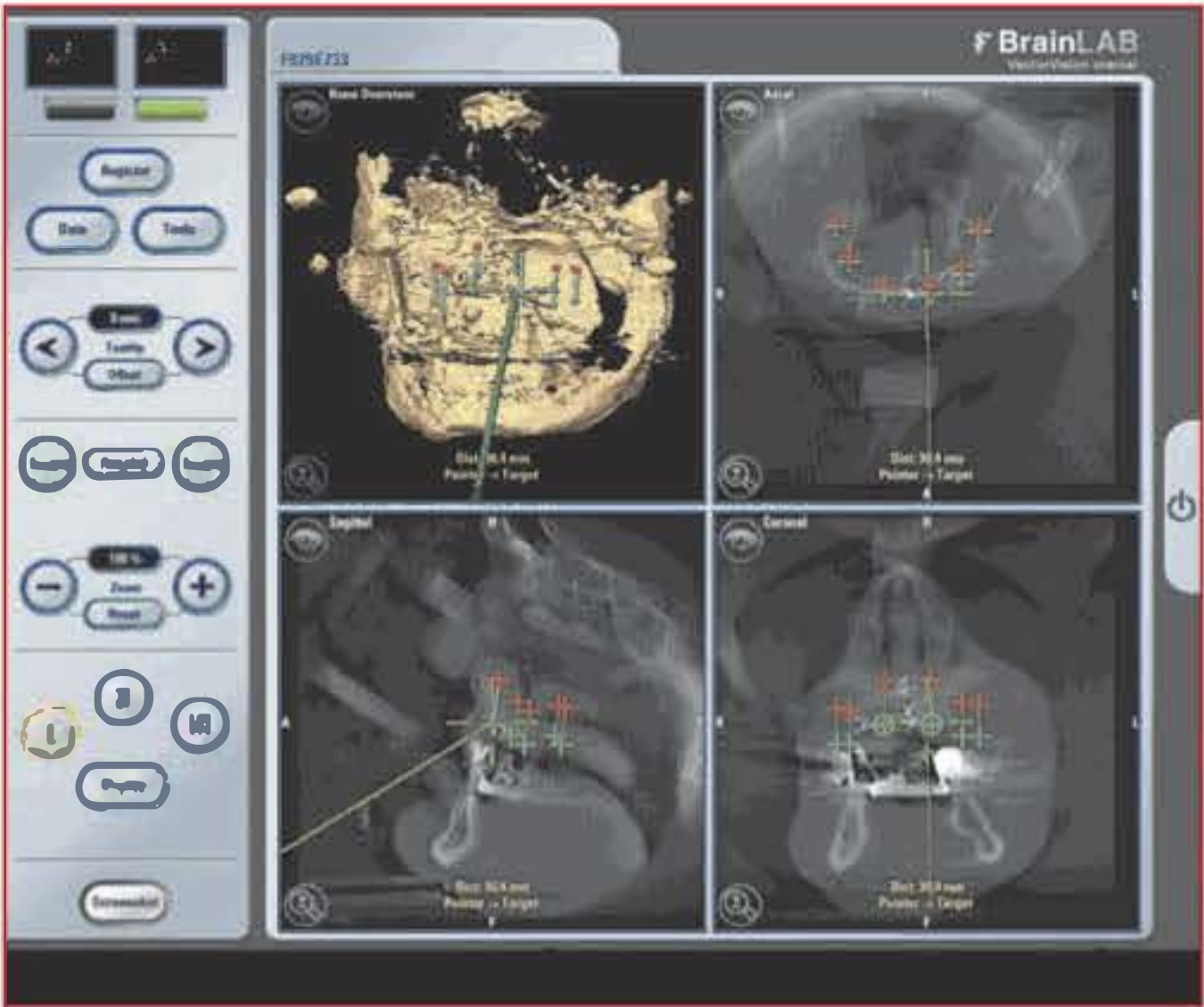


Fig 15-4f *The navigation system shows good agreement between the clinical situation and the surgical plan.*

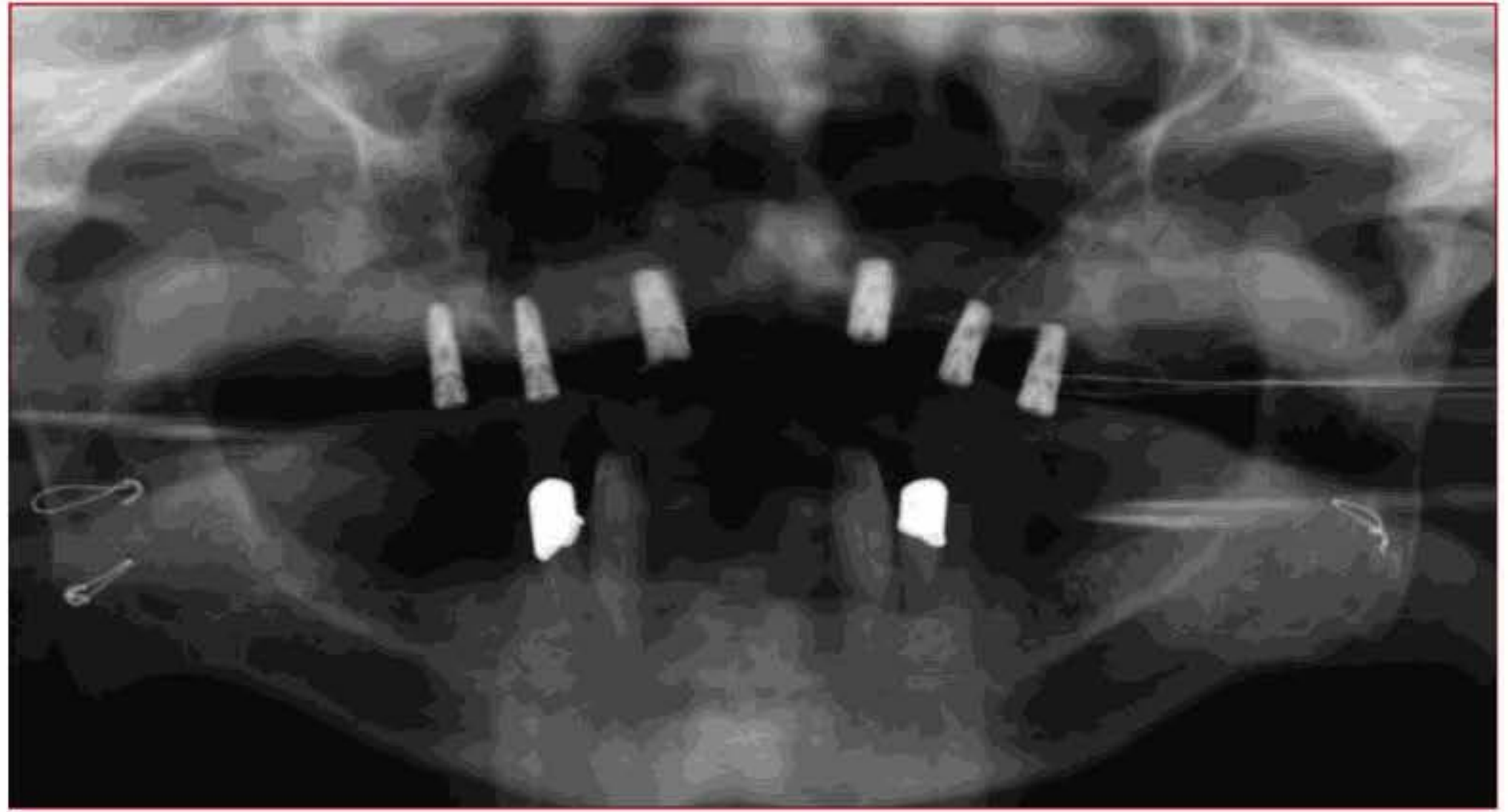


Fig 15-4g The postoperative OPT scan indicates a successful implantation despite the difficult anatomical situation.

The use of CBVI data for intraoperative navigation places certain requirements on the user that must be met for the process to succeed. For one thing, the lesion to be treated must be easily represented on the CBVI images. Low-contrast structures such as solid tumors in soft tissue are difficult to delineate with the physical characteristics of current cone-beam technology and should be visualized using conventional CT or MRI. In addition, the entire lesion must lie within the scan volume of the device (15 cm by 15 cm by 15 cm for GALILEOS). This may not be the case with disseminated foreign bodies, for example resulting from gunshot injuries.

Keeping in mind these limitations, CBVI technology can be considered a valuable alternative to CT for the purposes of intraoperative navigation. It enables simple 3D imaging that can be used for imaging-guided surgery in the oral and maxillofacial area without requiring expensive and large radiological equipment. Additionally, radiation exposure for the patient is significantly reduced compared with conventional CT imaging.

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16 Maxillary Surgery Using Cone-beam Volumetric Imaging

Robert A. Mischkowski and Max Zinser

The use of computers to assist surgery and the introduction of CBVI as a supportive modality represents a paradigm shift in orthognathic surgical approaches.

16.1 Computer-assisted Orthognathic Surgery

The general foundations of orthognathic surgery are discussed in this chapter. Moreover, novel, computer-assisted 3D methods of virtual surgical planning will be introduced. The traditional planning based on 2D x-ray images will be replaced by modern 3D CBVI images.

Surgical orthodontics includes all surgical bone relocation procedures to correct congenital or acquired jaw malpositions (dysgnathias) with functional disruptions of the chewing mechanism or deformities in the facial region.

According to current etiological research, most dysgnathias are “multifactorial with additive polygenic” origins. Considerable regional differences have been observed; in southern Germany, for example, the overdevelopment of the mandible (class III) is found much more frequently than in northern Germany.¹

Classification and definition

Depending on the origin, dental and skeletal malpositions can be distinguished.

Dental malpositions are divided into three classes, according to Angle:

- class I: eugnathic (normal) dentition
- class II: distocclusion
 - 1: with protruded front teeth
 - 2: with deep bite
- class III: mesiocclusion.

Facial skeletal anomalies occur symmetrically or asymmetrically and/or affect the maxilla or mandible. They are generally differentiated into hyperplasia and hypoplasia.

16.1.1 Diagnosis, Planning and Treatment Concepts

A traditional concept based on 2D images can be distinguished from new 3D computer-assisted methods. The former requires the manufacture of surgical splints by the dental technician; the latter allows direct manufacturing through rapid prototyping technology.²

The traditional concept

The traditional planning of orthognathic surgery is based on 2D x-ray images. Through cephalometric imaging, the positional relationship of the maxilla and mandible is identified and meas-

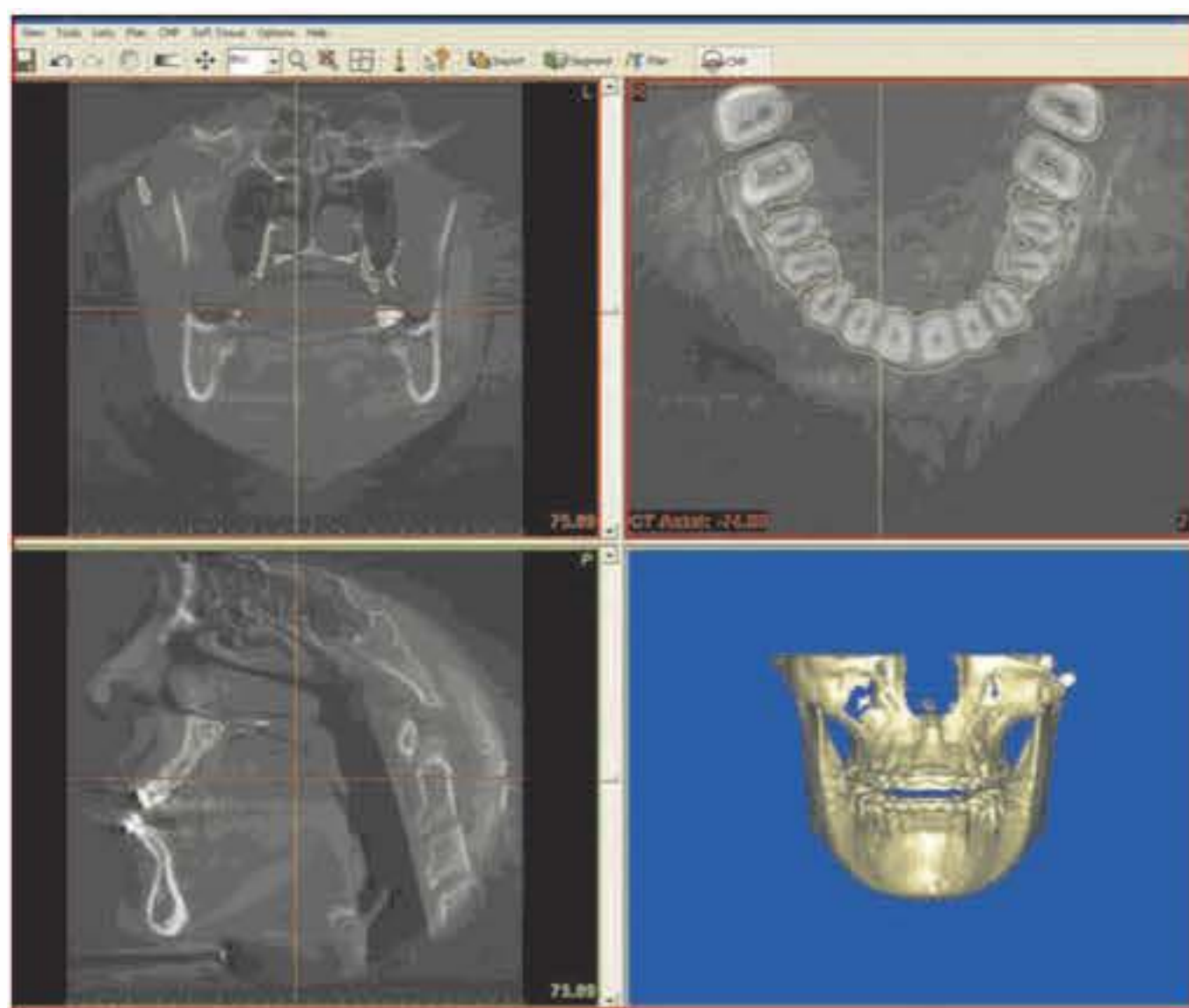


Fig 16-1 Dysgnathia (prognathism with open bite): preoperative data set, axial slices and 3D display (CMF planning module Simplant Pro 9.21 Materialise, Leuven, Belgium).

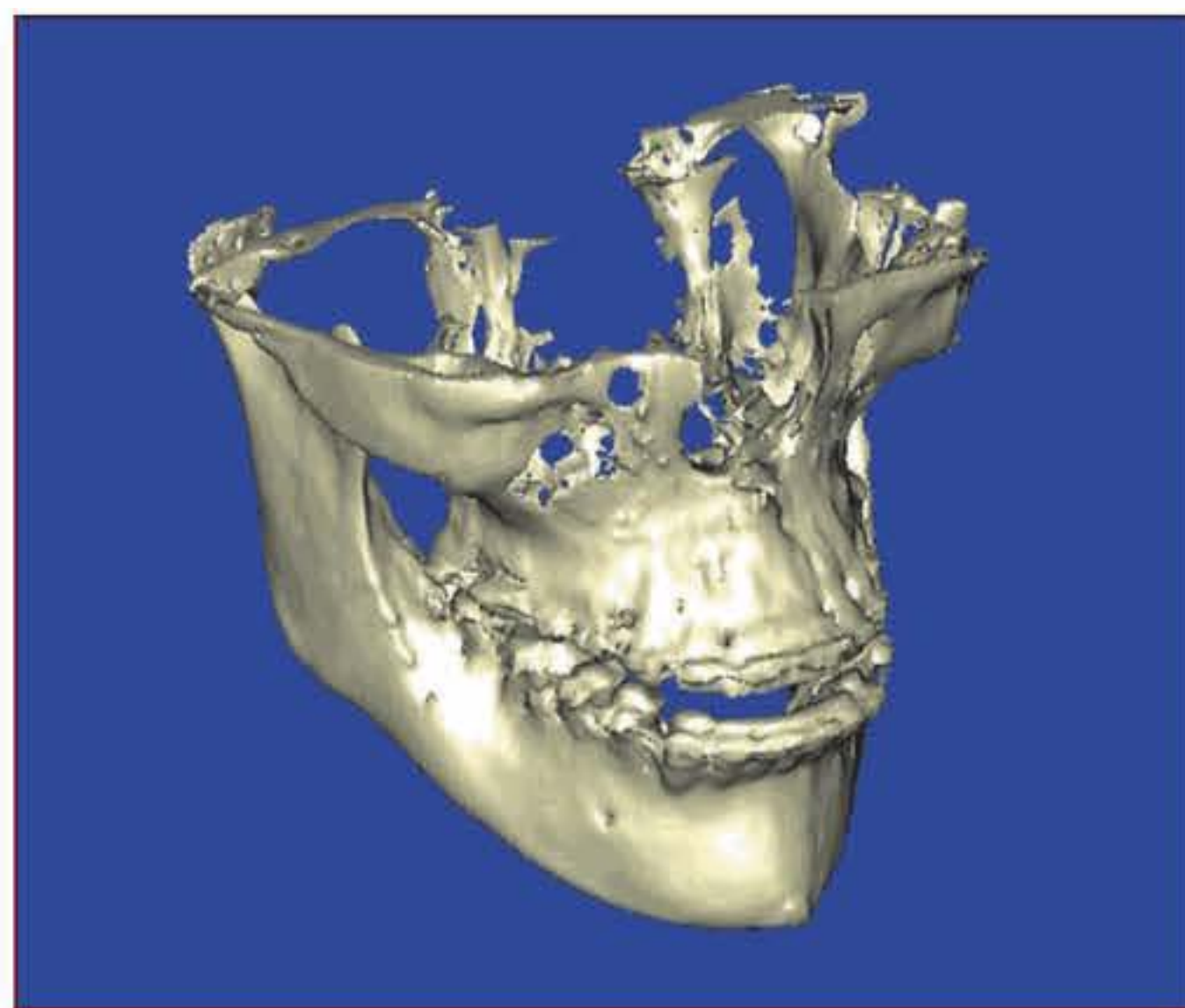


Fig 16-2 Dysgnathia (prognathism with open bite): preoperative data set, axial slices and 3D display (CMF planning module Simplant Pro 9.21 Materialise, Leuven, Belgium).

ured. The teeth are evaluated in an orthopantograph (OPG) and a plaster model analysis of each jaw is required. The clinical and esthetic profile of the patient as well as the cephalometric analysis influence the treatment plan. The surgical plan is implemented using surgical splints that are manually made by the technician in the dental articulator.

Computer-assisted planning

In recent years, computer-assisted surgical methods in the head and neck area have been continuously advanced. Initially, optical navigation methods were the exclusive focus. Clinical applications pertained mainly to tumor surgery. Improvements in the software now permit their application in reconstructive and craniomaxillofacial (CMF) surgery.³⁻⁹ CMF planning modules facilitate a virtual 3D representation using CBVI data sets. Additional imaging is then unnecessary. The examination and diagnostics of facial asymmetries has been significantly simplified using 3D imaging. Moreover, all surgical steps can be preoperatively planned in a virtual environment.^{10,11} With the aid of bone- and tooth-supported cutting and drilling templates drafted on the computer, so-called "SurgiGuides", the results of the planning can be transferred exactly to the surgical procedure. Surgical splints can be produced in a direct manufacturing process using rapid prototyping. The individual steps and work processes are explained with the aid of the following example.

16.1.2 Example of an Orthognathic Operation Using Cone-beam Volumetric Imaging

Initial examination and diagnostics

A CBVI data set (GALILEOS) is prepared preoperatively. This data set is stored in DICOM format and can be directly implemented in the planning module (CMF Simplant Pro 9.21). The data sets can be displayed in combination as a 2D image (axial, coronal and sagittal) and as a freely movable 3D image, as shown in Figures 16-1 and 16-2.

All diagnostics can be carried out using the 2D images or the 3D display. The diagnostic findings include information on tooth position, evaluation of apical bases, the skeletal bone situation, the position of the jaws with respect to the cranial base, the existing bone availability, the profile of the nerves, etc. In addition, the CMF planning unit permits toggling between the axial tomographs and the traditional dental images, the cephalometric image and the OPC.

Defining the planes of symmetry

In most facial asymmetries, the basal skull plane represents a constant base that is not involved in asymmetrical changes. This horizontal (axial) base plane (basal skull) is established by the sella and two infraorbital points (Figure 16-3). The individual points can be defined in both the 3D and the 2D images (Figure 16-4). In addition, a second plane is constructed perpendicular to the cranial base plane through the nasion (N). The result is a coordinate system that corresponds to the established treatment objective or ideal facial symmetry.

In the next step, the "current situation" – the extent of existing deviation – is determined on the established coordinate system (the patient's ideal symmetry). First, the occlusal plane is drawn in. It runs through one frontal and two molar contact points (Figure 16-5). Perpendicularly to the occlusal plane, the "real" midfacial plane is determined through the incisal point.

In the next step, the "ideal" and "real" planes of symmetry are superimposed (Figure 16-6). This provides the distances and directions for correction – the displacement vectors – to obtain the patient's ideal symmetry in alignment with the cranial base.

The operational method is selected based on the patient's ideal symmetry. In the clinical example shown, the ideal position is obtained via a bimaxillary corrective osteotomy designed to tilt the maxilla cranially on the left side, rotate it to the left, and to compensate the sagittal discrepancy via forward-shifting with simultaneous caudal tipping to correct the open bite. The mandible will be opposed in accordance with the occlusion of the maxilla.

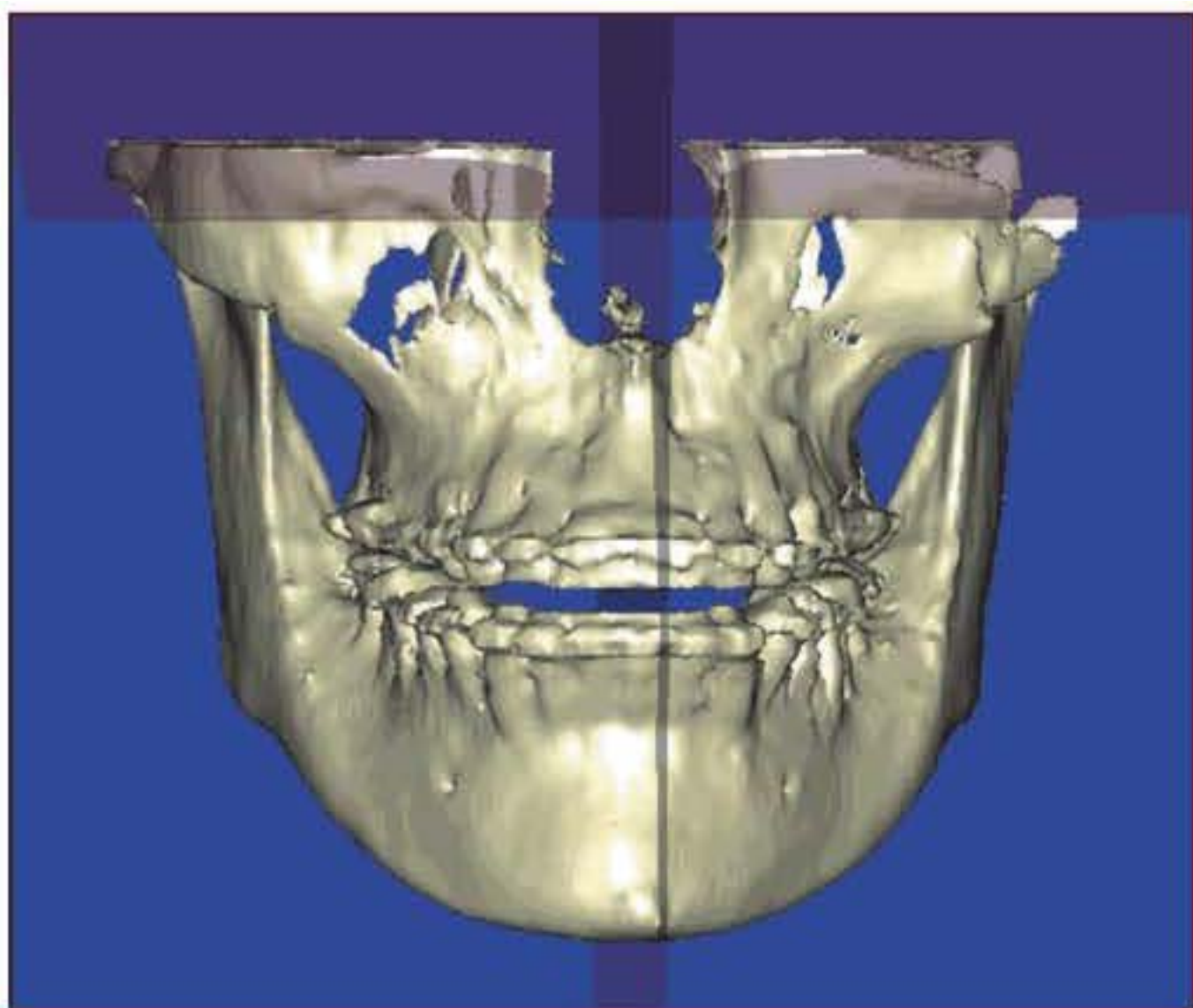


Fig 16-3 Definition of patient's ideal facial symmetry. The cranial base plane is established using the sella and two infraorbital points. The ideal midfacial plane is drawn in perpendicularly to the cranial base line through the nasion.

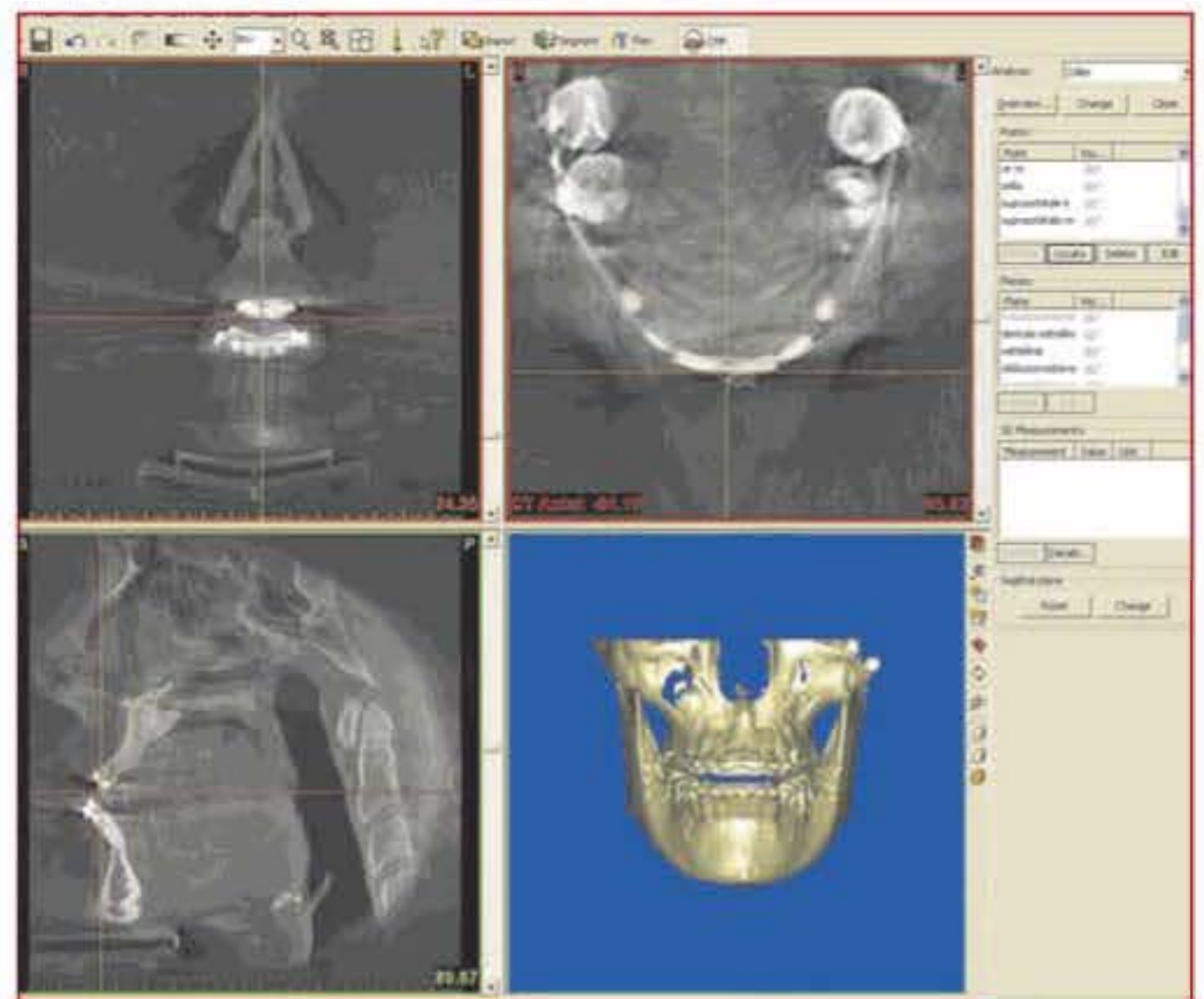


Fig 16-4 Definition of patient's ideal facial symmetry. Drawing in and marking the points using the 2D and 3D images; definition of the nasion.

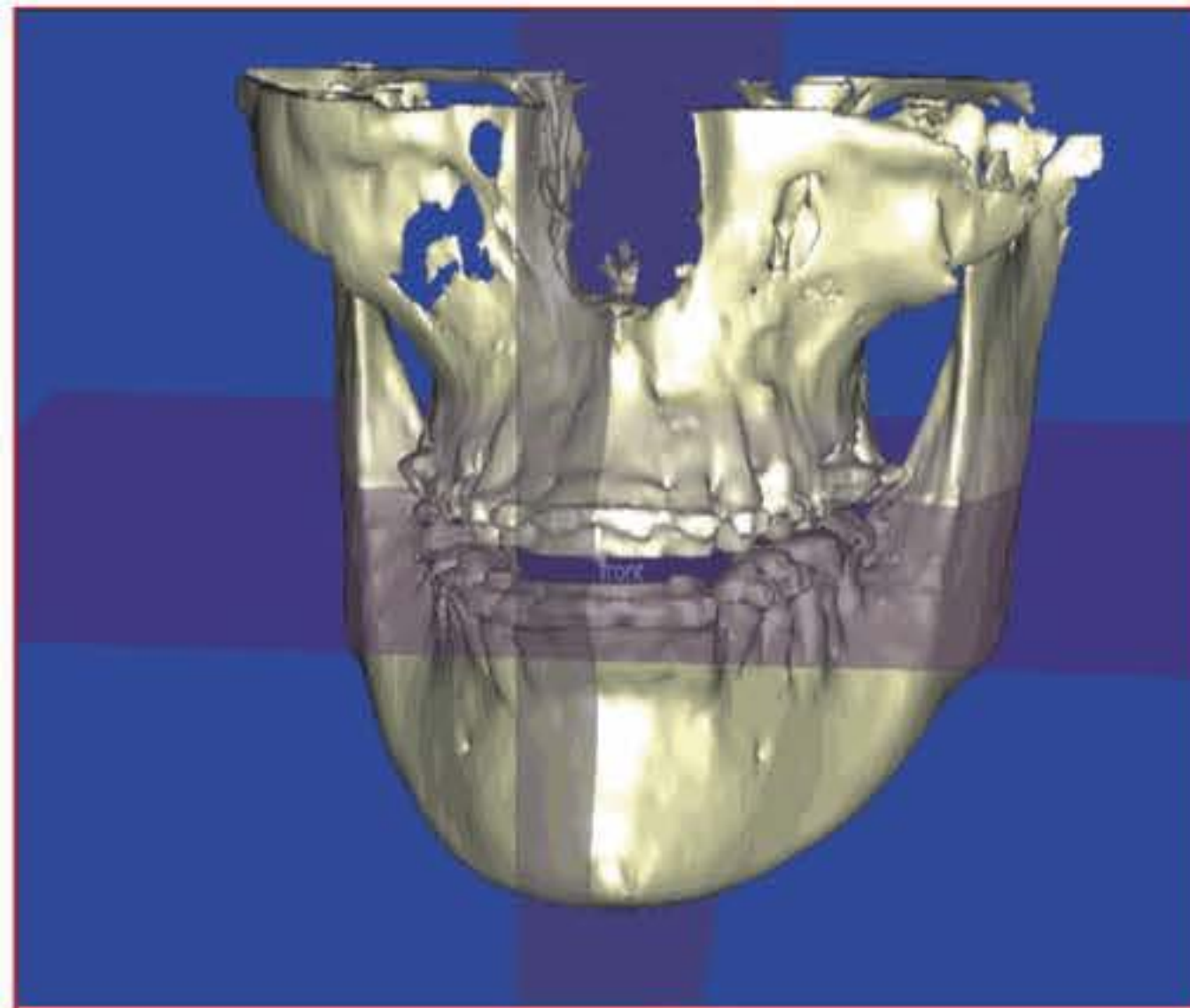


Fig 16-5 Determination of the "real facial symmetry", defined by the occlusal plane and the midfacial plane going through the frontal incisal point.

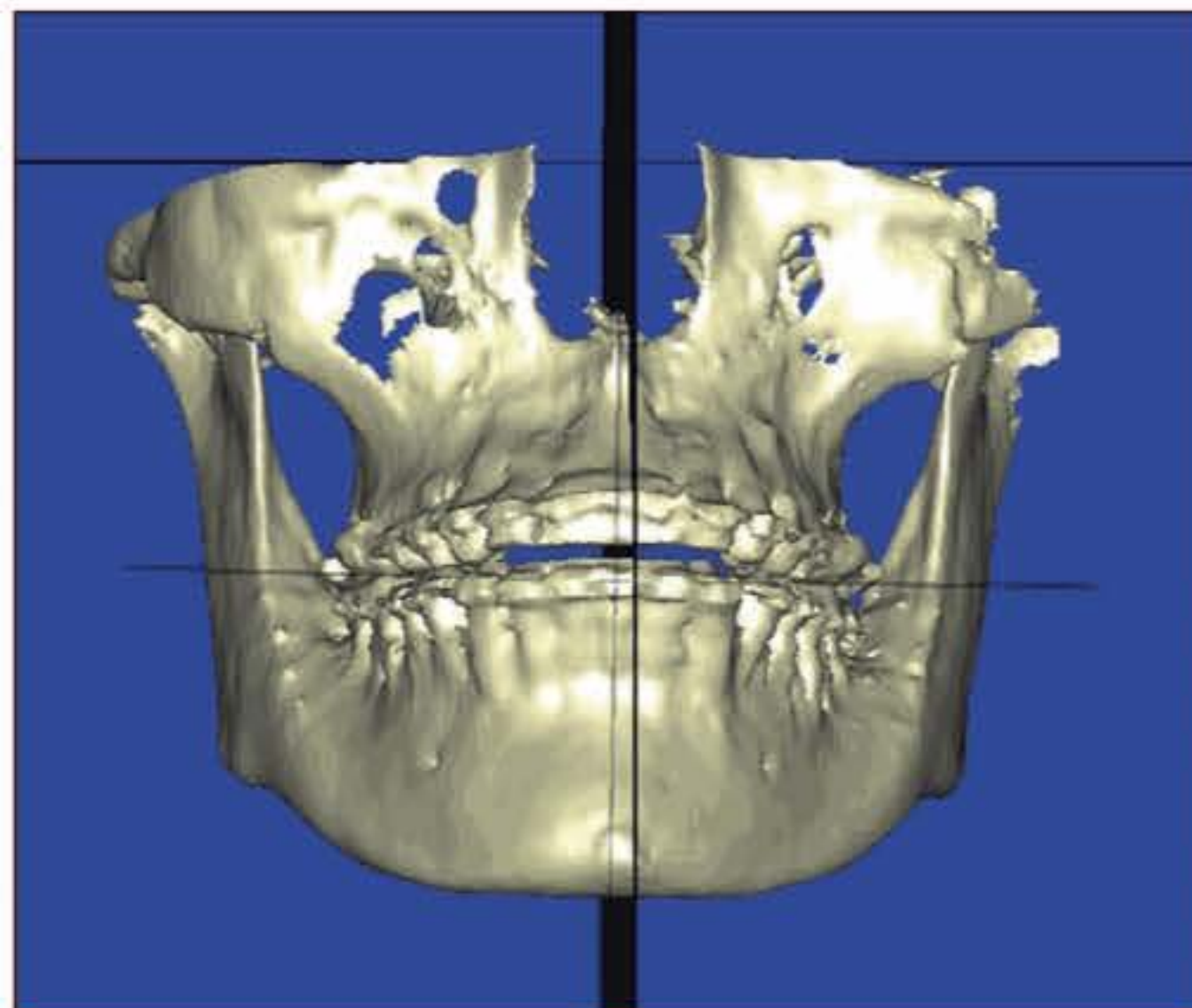


Fig 16-6 Superimposed "ideal" and "real" facial symmetry.

Segmentation of bones, surgical planning

The CMF software module Simplant 9.21 facilitates any desired segmentation of bone parts. The cutting plane can be determined individually in the Le Fort I plane (Figure 16-7). In the same manner, the cutting planes for the sagittal split are determined in the mandible (Figure 16-8). Segmented bone parts result, which can be freely spatially moved independently of one another. This facilitates virtual surgical planning (Figure 16-9).

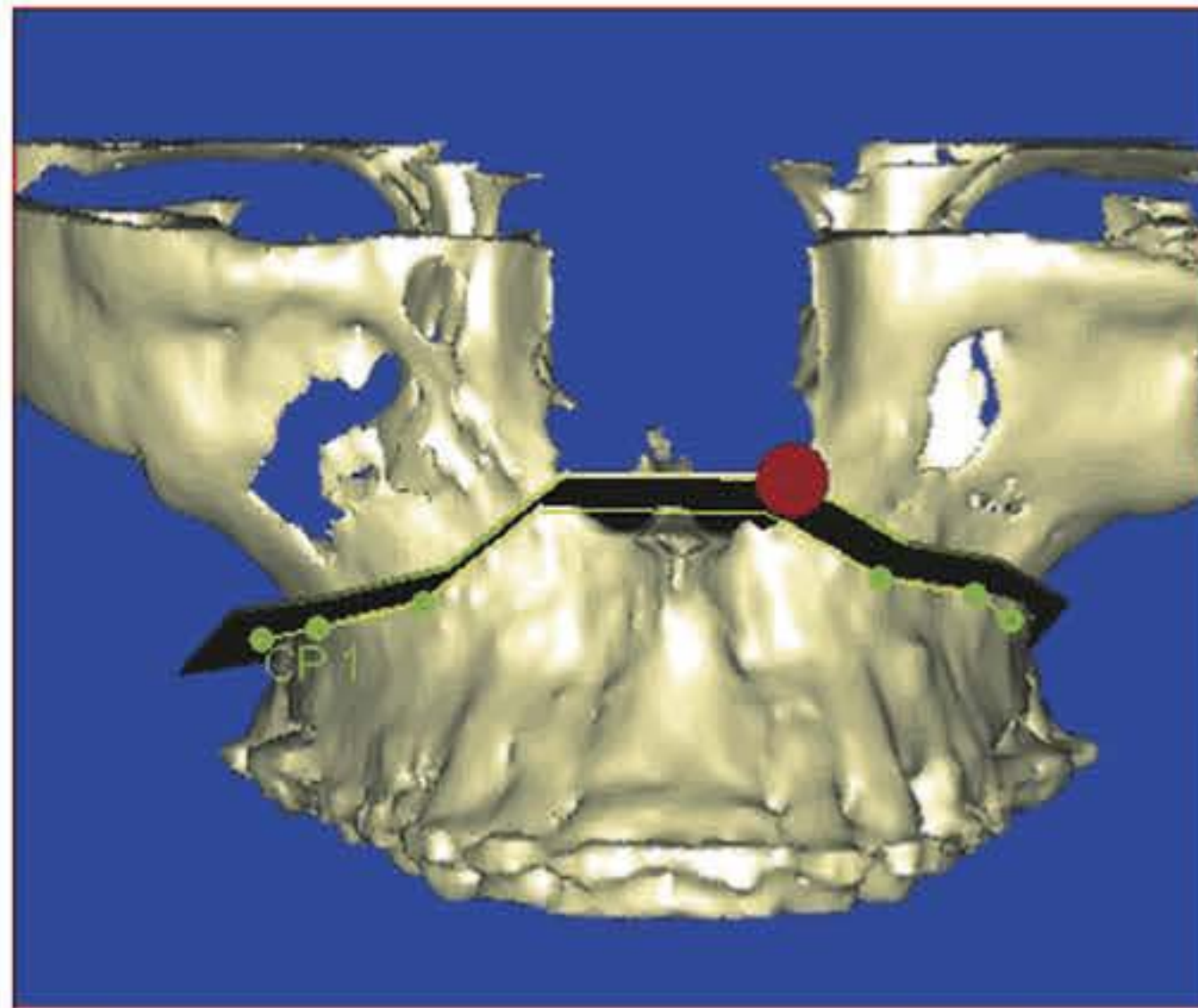


Fig 16-7 Segmentation of the maxilla on the Le Fort I level in the 3D CBVI data set.

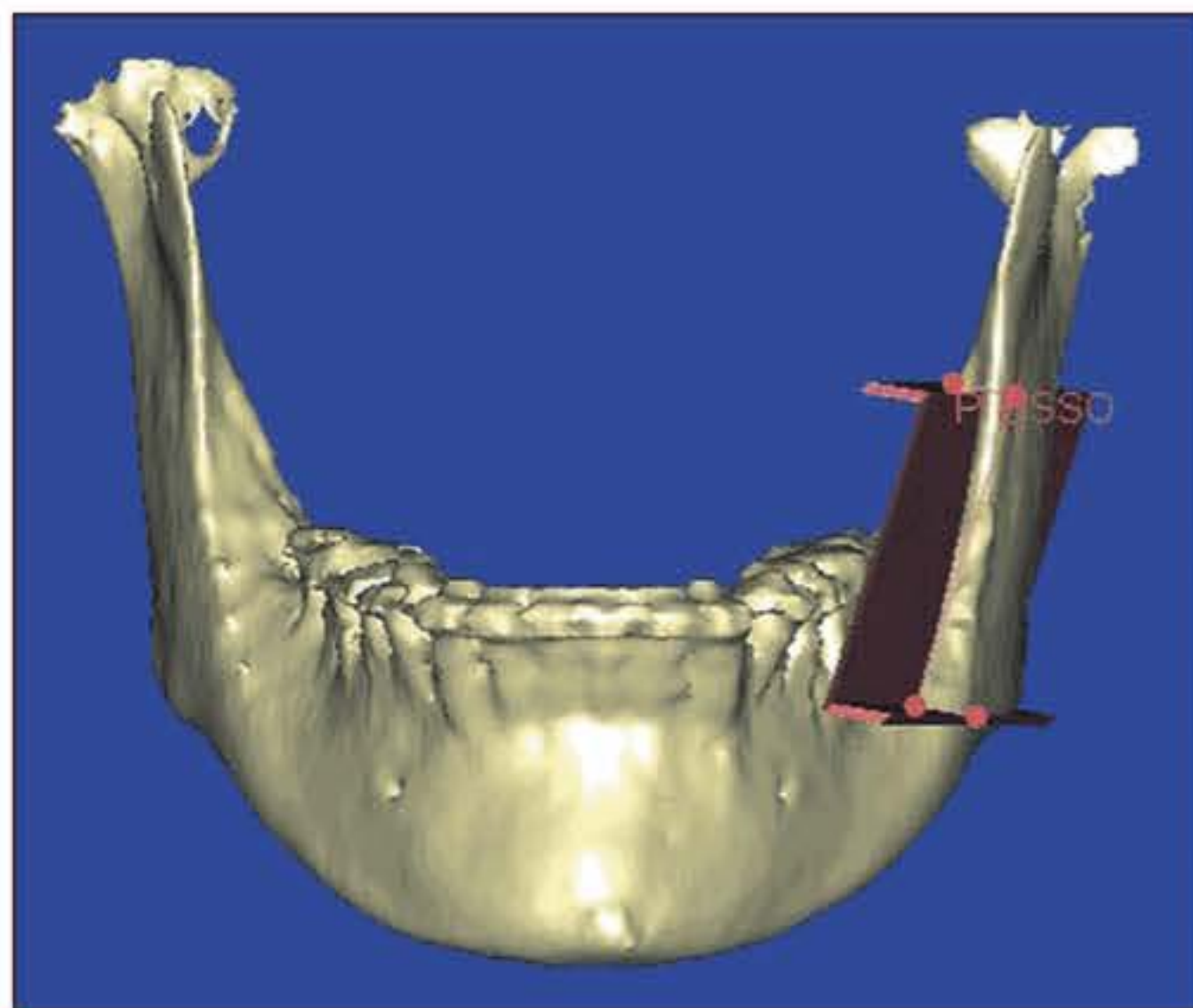


Fig 16-8 The 3D CBVI data set of the mandible. Segmentation of the mandible representing the cutting plane of a Obwegeser-Dal-Pont sagittal split surgery.

Transposition of bone segments, virtual surgical planning

After establishing the surgical technique and segmentation of the bone segments to be moved, the planes of symmetry are once again superimposed (Figure 16-10). The segmented bone pieces can be moved according to the patient's ideal facial planes (Figure 16-11). In the example shown here, the maxilla is first tilted cranially in the Le Fort I plane on the left side until the occlusal plane runs parallel to the cranial base. Then, it is rotated in the axial plane to reset the midfacial line. In

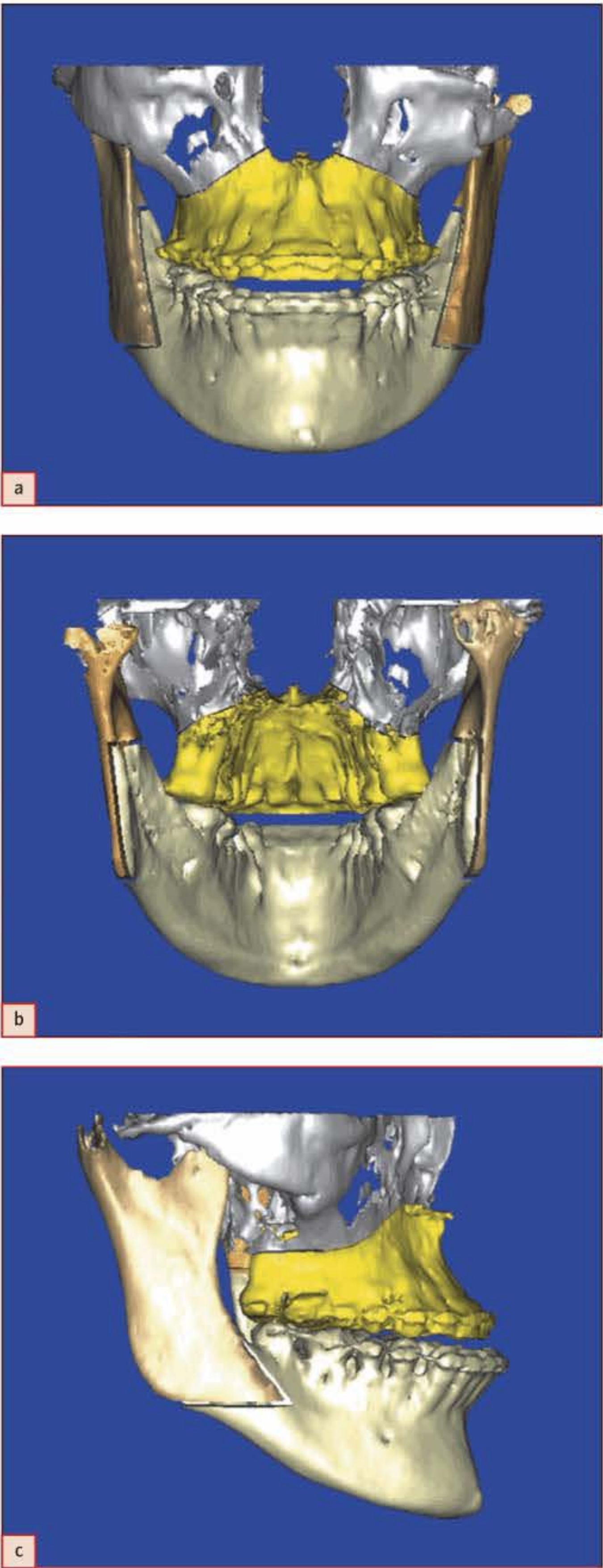


Fig 16-9 Segmented bone parts as a baseline for the virtual surgical planning: Le Fort I level in the maxilla and sagittal split in the mandible. Bone segments in the anterior (a), posterior (b) and sagittal (c) views.

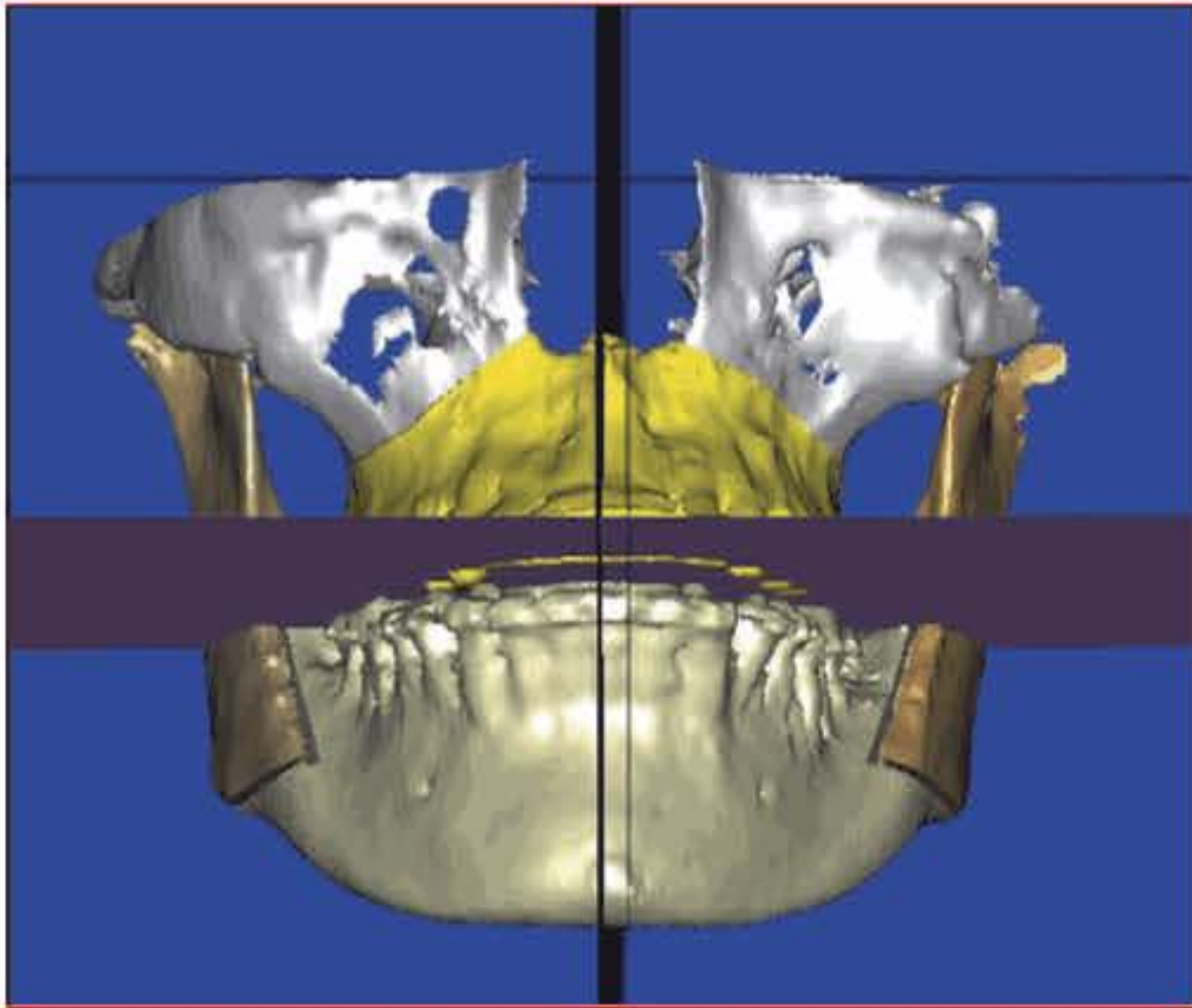


Fig 16-10 Superimposed planes of symmetry of "ideal" and "real" facial symmetries in segmented planning.

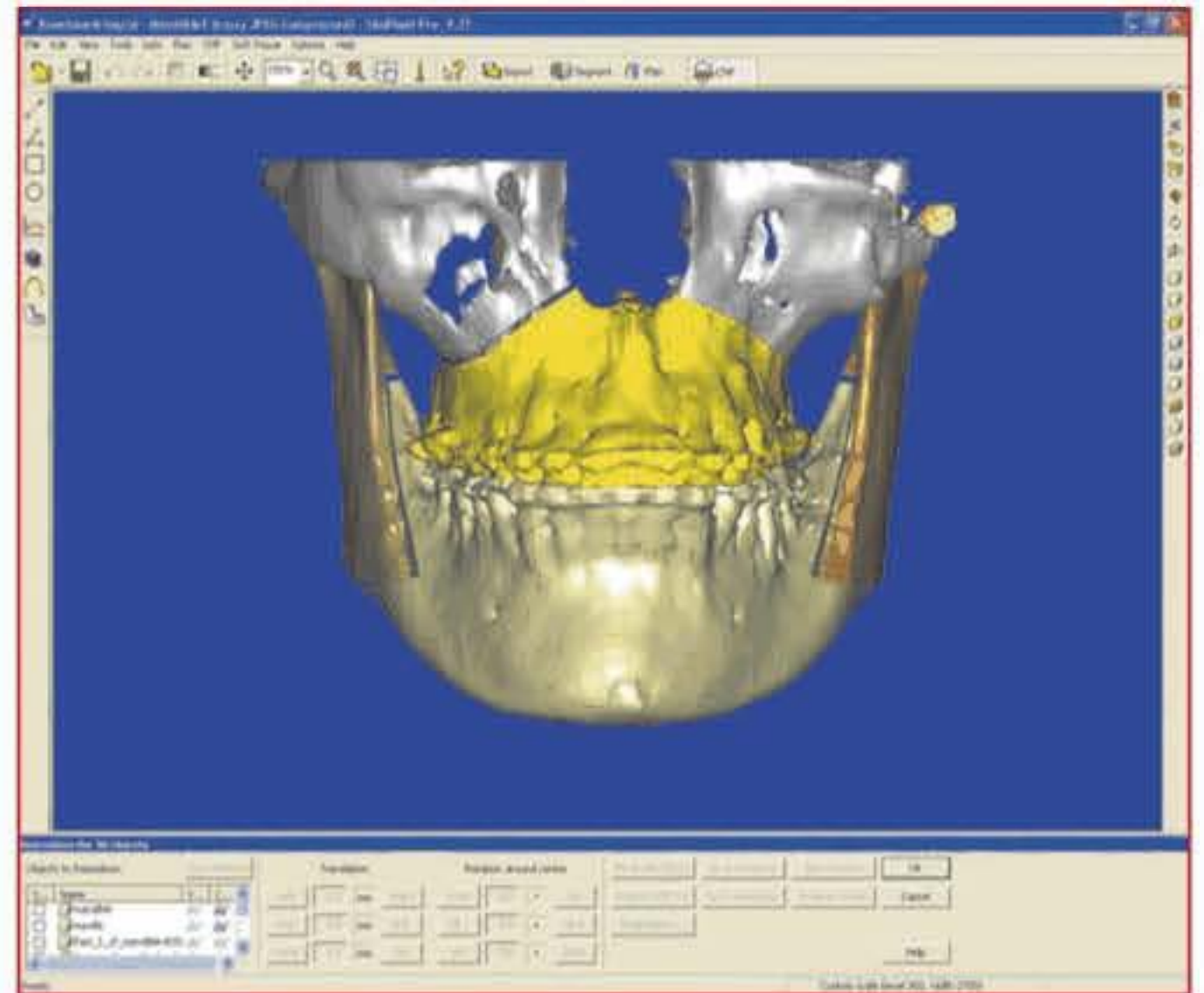


Fig 16-11 Software function "reposition of 3D objects". The segmented bone pieces can be moved individually for "virtual planning".

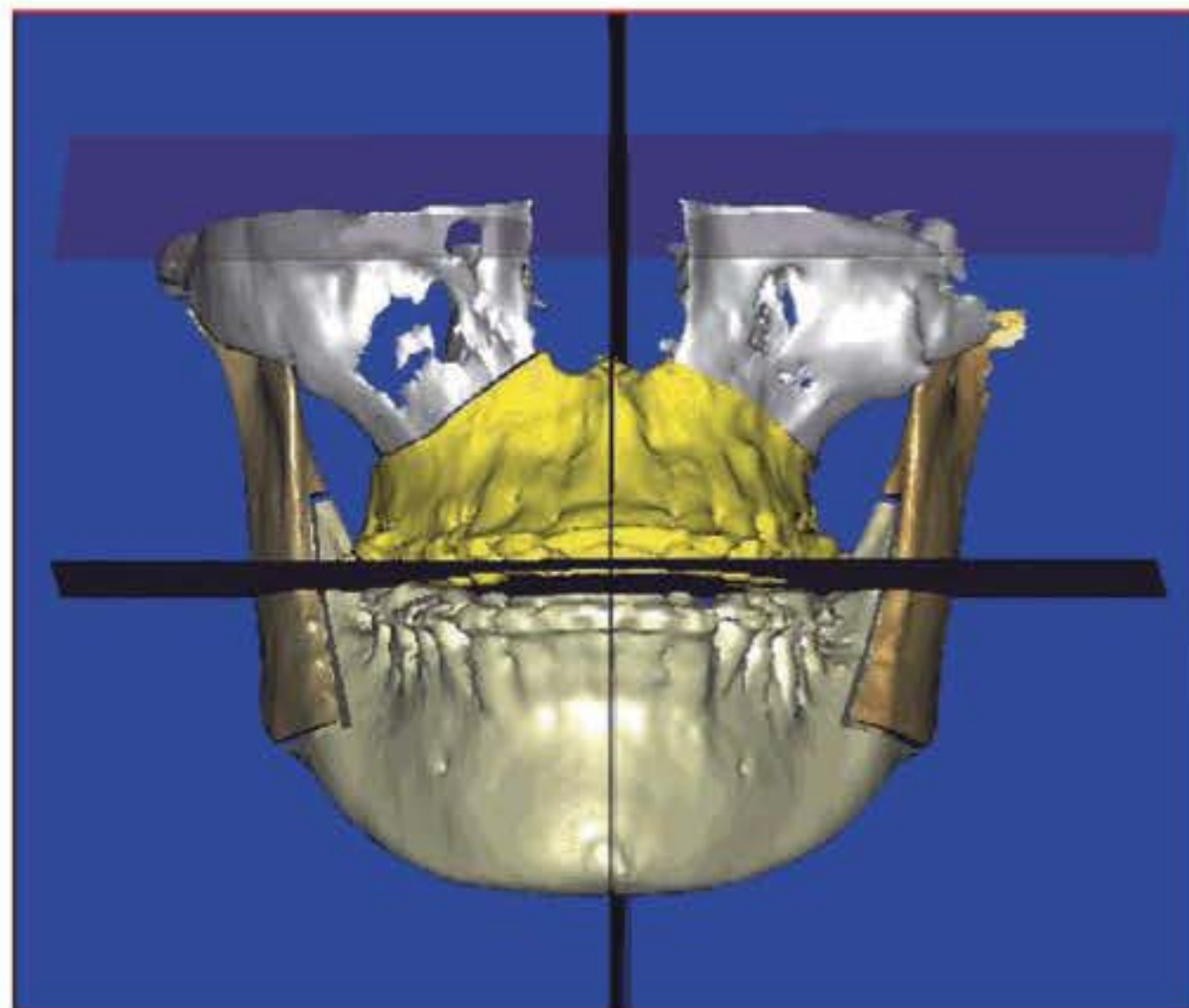


Fig 16-12 After transposition of the maxilla in the Le Fort I level, the real facial symmetry corresponds to the ideal, designed facial symmetry.

the last step, the maxilla is then shifted 3 mm anteriorly and tilted 2 degrees caudally to compensate the prognathism of the mandible and the retroinclination of the maxilla. In the end, the "real" facial asymmetry matches the ideal "designed" facial asymmetry (Figure 16-12).

After virtually positioning the maxilla, the mandible is arranged (Figures 16-13 to 16-15). The planning program gives the option of moving the mandible individually and aligning it with the maxillary dentition. This step corresponds to model analysis or model surgery in the articulator using plaster models in traditional surgical planning.

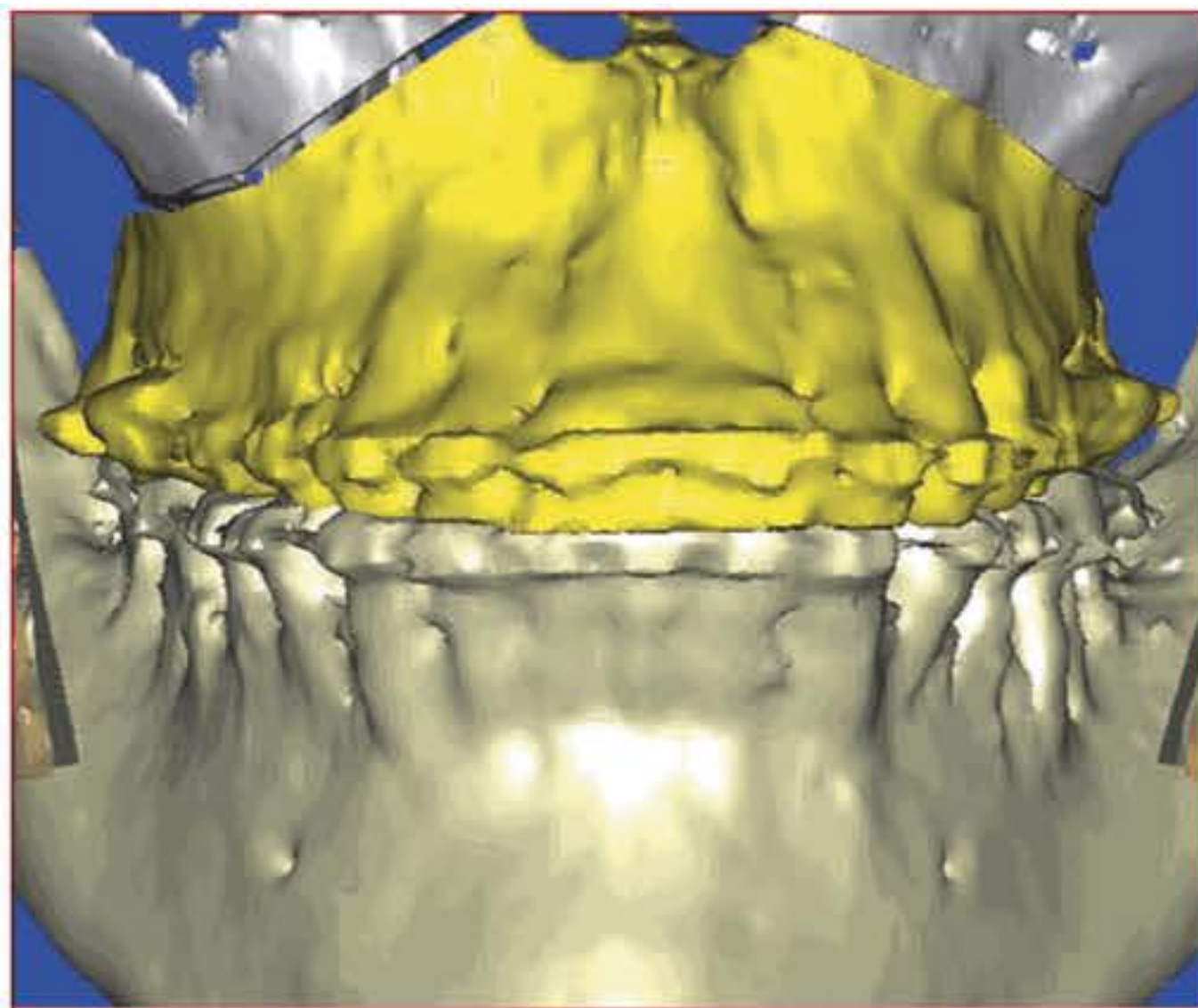


Fig 16-13 Positioning of the mandible with respect to the maxilla corresponding to the occlusion, anterior view.

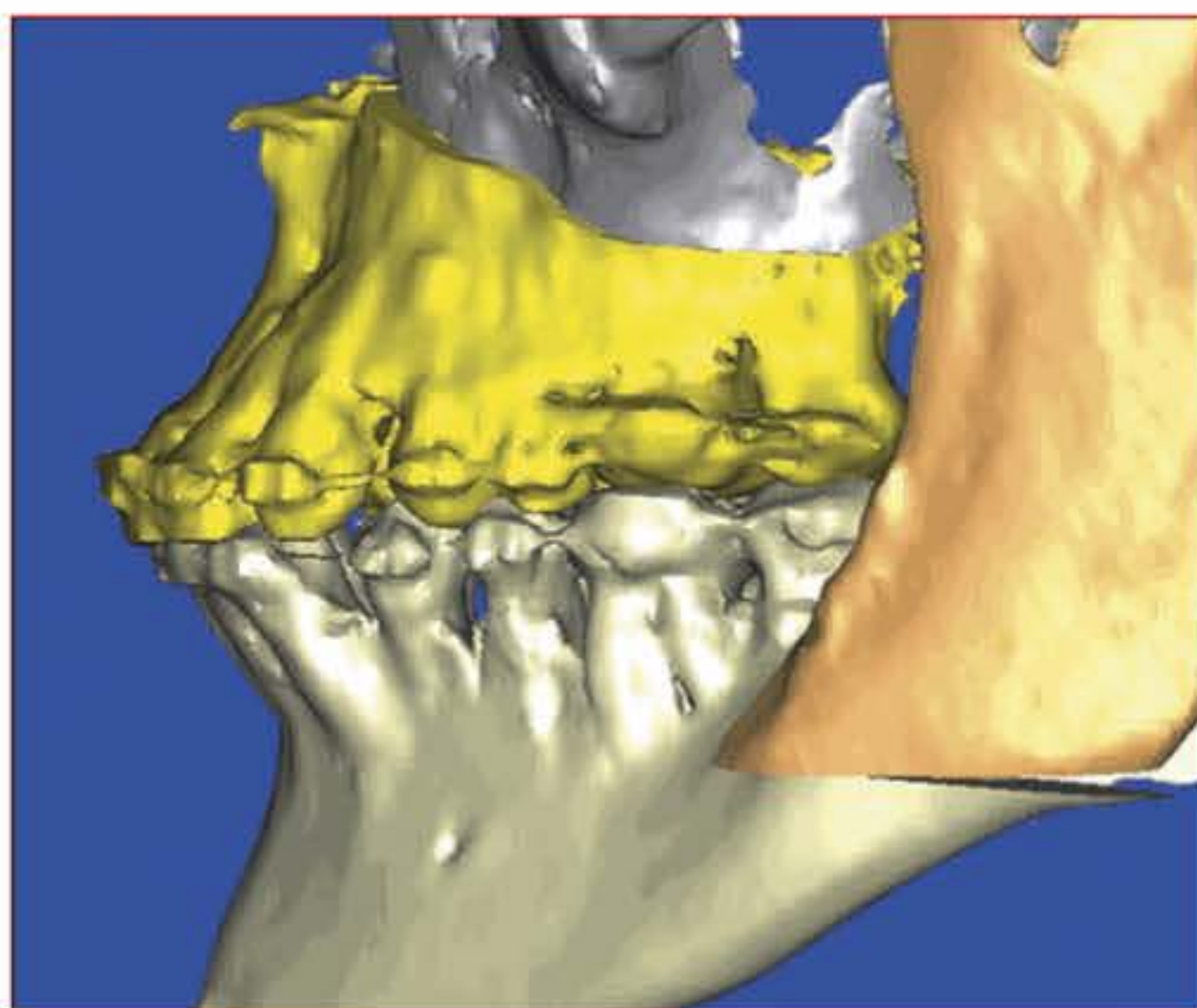


Fig 16-14 Positioning of the mandible with respect to the maxilla corresponding to the occlusion, lateral view.

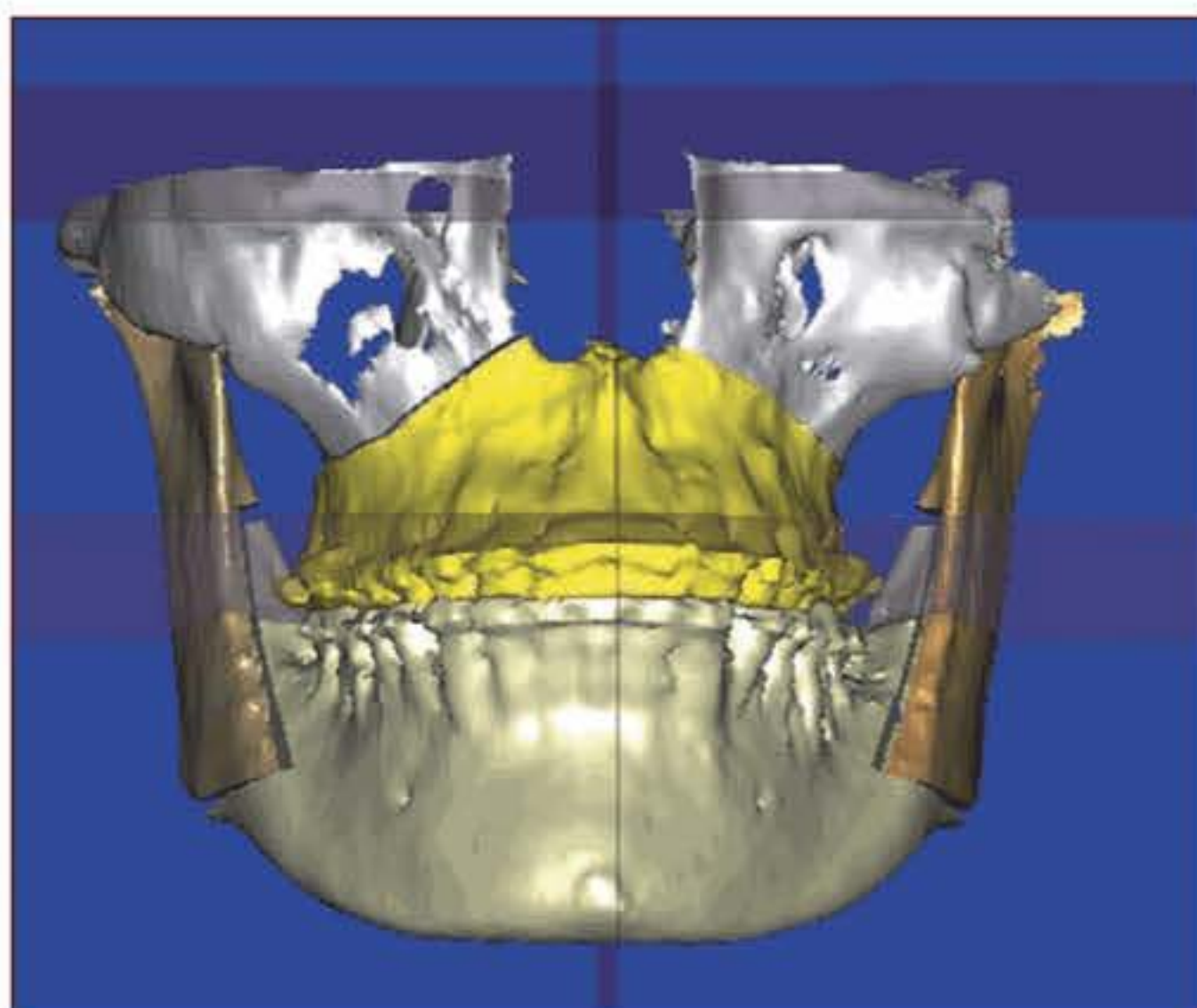


Fig 16-15 Final result of virtual surgical planning; the "real" plane of symmetry corresponds to the "designed, ideal plane of symmetry" (see Fig 16-16).

Results of virtual planning

The virtual CMF planning module facilitates exact 3D representation of the bone segments. Moreover, the movements of the segments can be precisely analyzed. In the example shown, the transposition analysis yielded the following values (Figures 16-16 to 16-21):

Maxilla:		Mandible:	
Anterior transposition	3 mm	Dorsal transposition	4 mm
Caudal shift	2°	Cranial transposition	2 mm
Coronal rotation	1° dorsally	Rotation in the x-axis	5° cranial
Rotation in the z-axis	4° mesially		

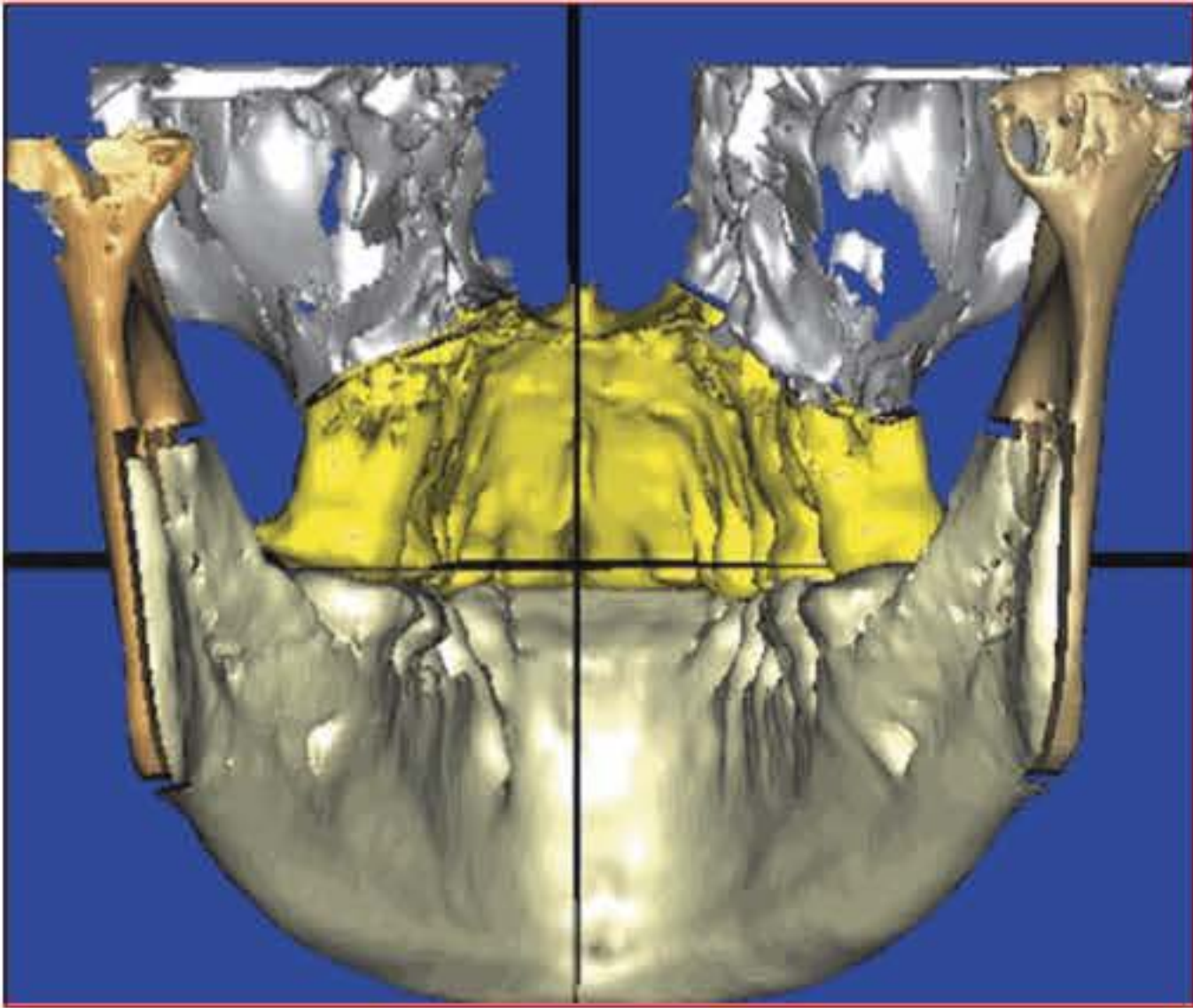


Fig 16-16 Conclusion of virtual planning: the facial symmetry corresponds to the ideal design, dorsal view.

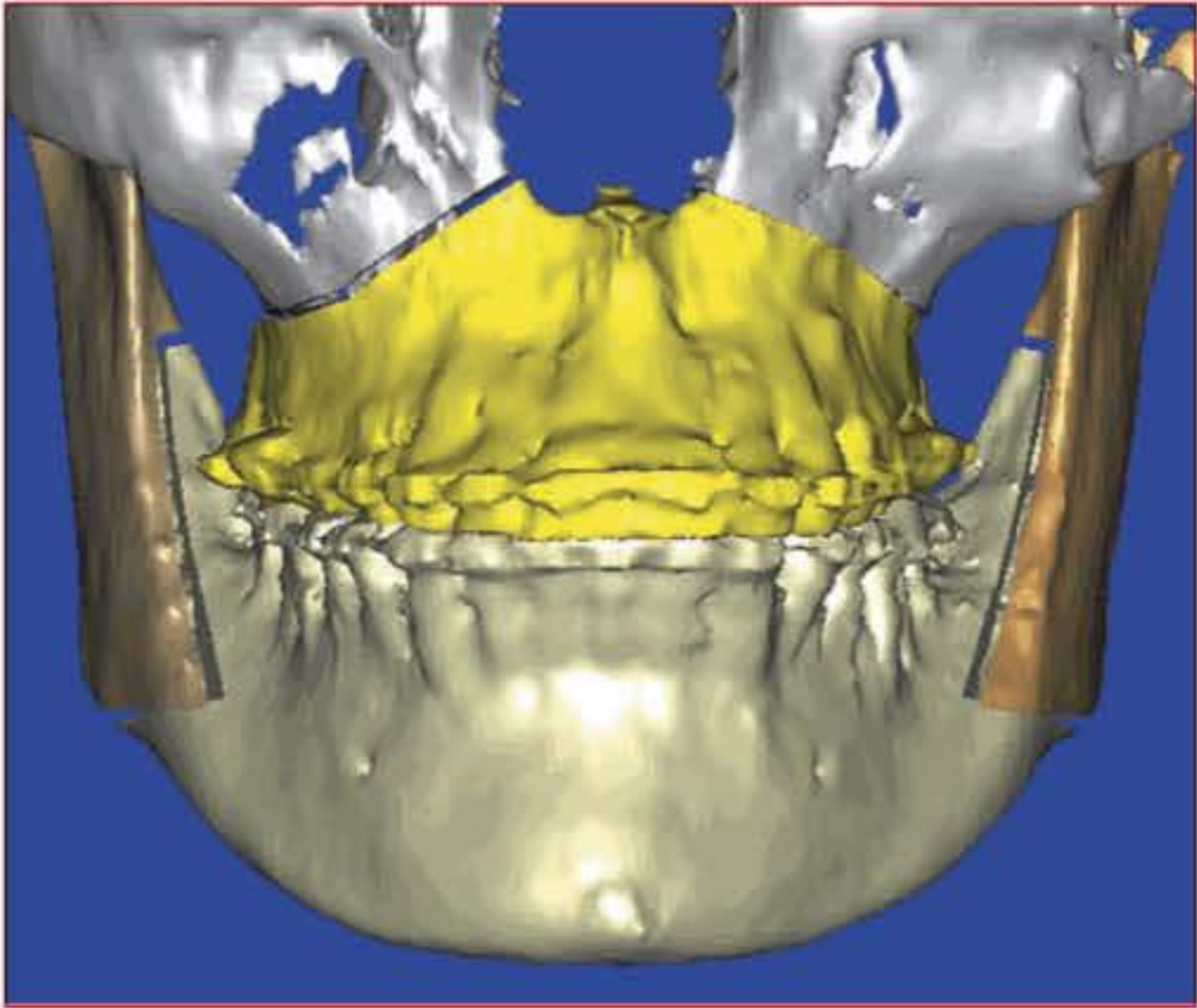


Fig 16-17 Conclusion of virtual planning, anterior view.

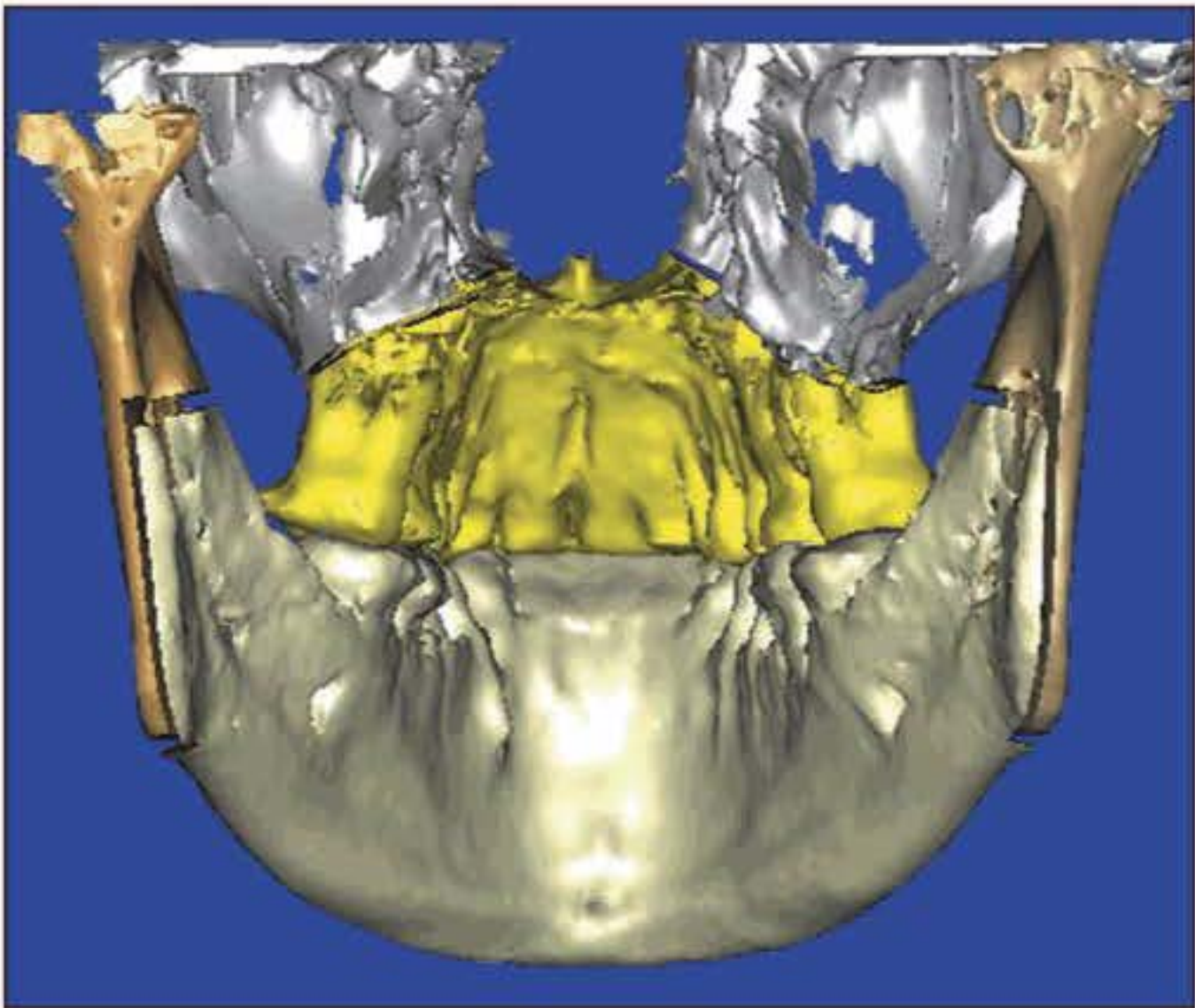


Fig 16-18 Conclusion of virtual planning, posterior view.

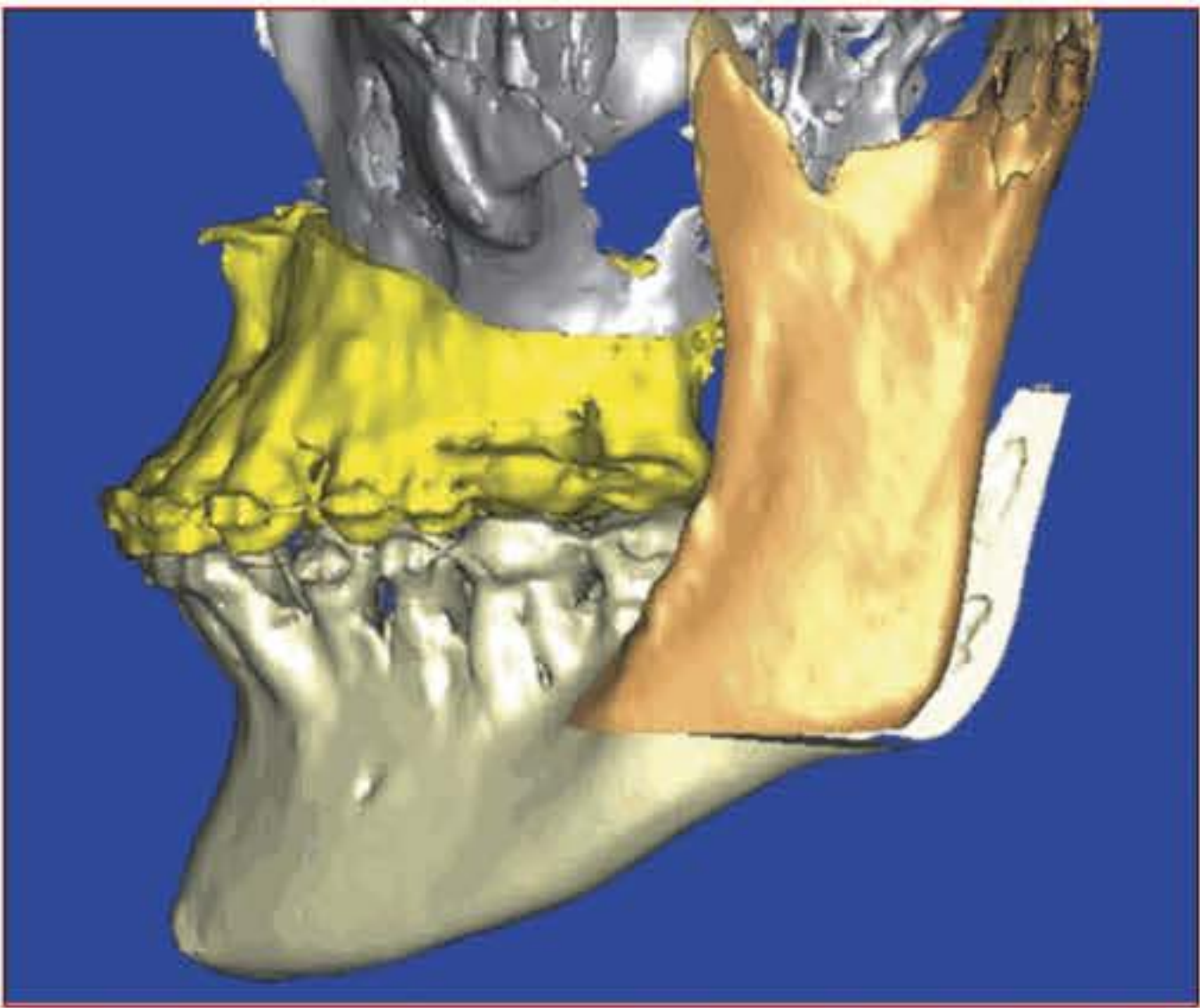


Fig 16-19 Final result of virtual planning, lateral view.

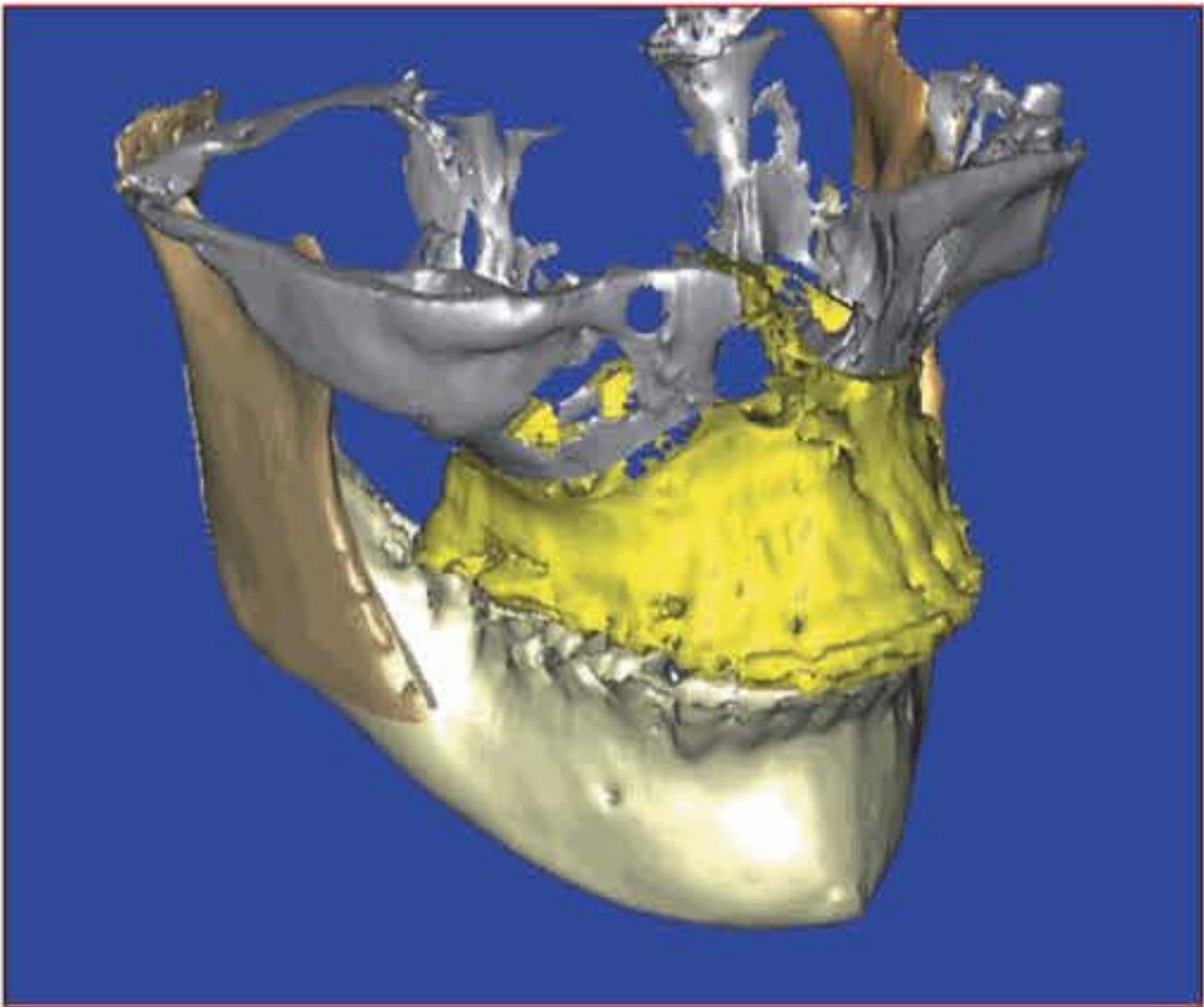


Fig 16-20 Final result of virtual planning, isometric display.

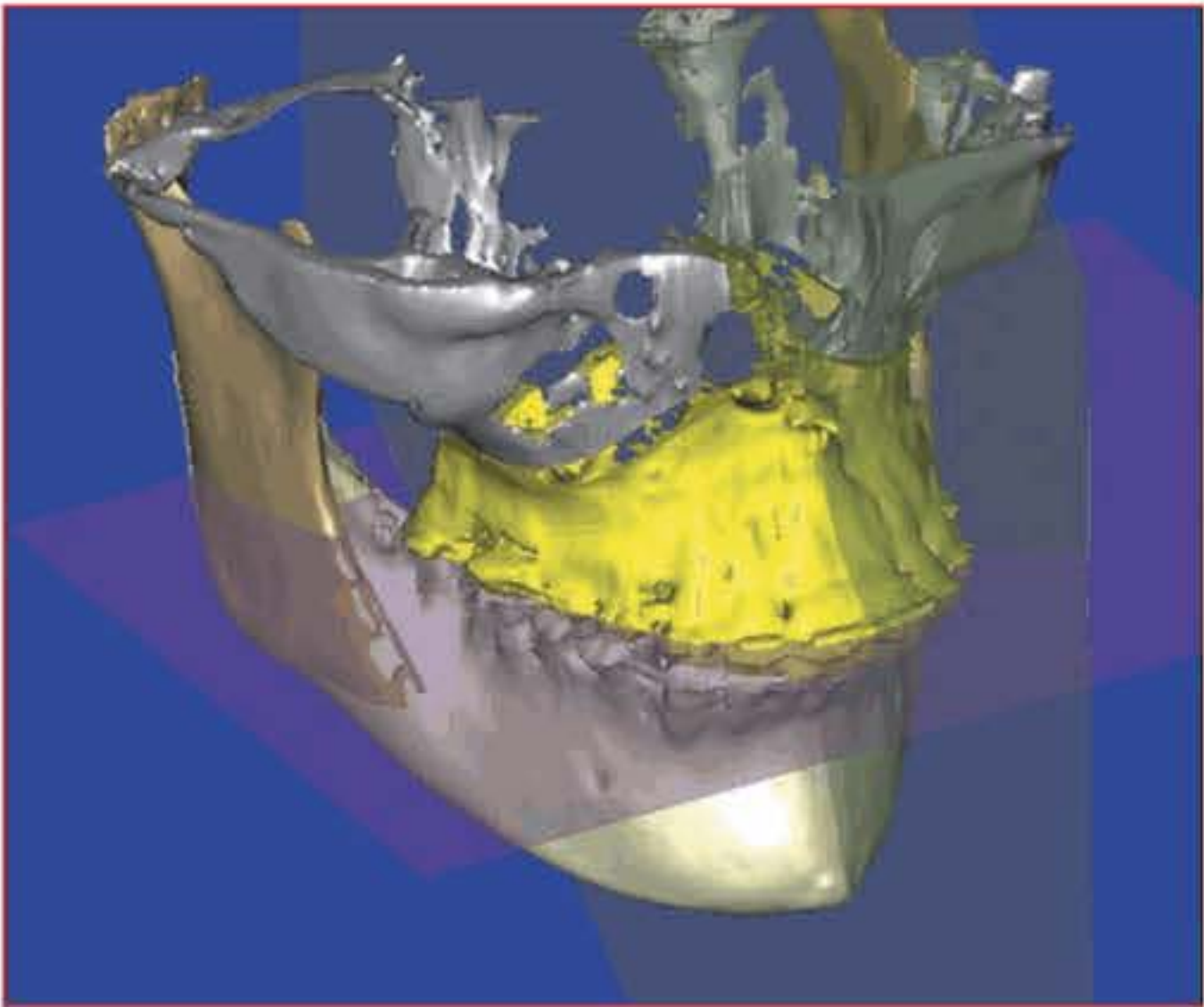


Fig 16-21 Final result of virtual planning, isometric representation with superimposed planes of symmetry.

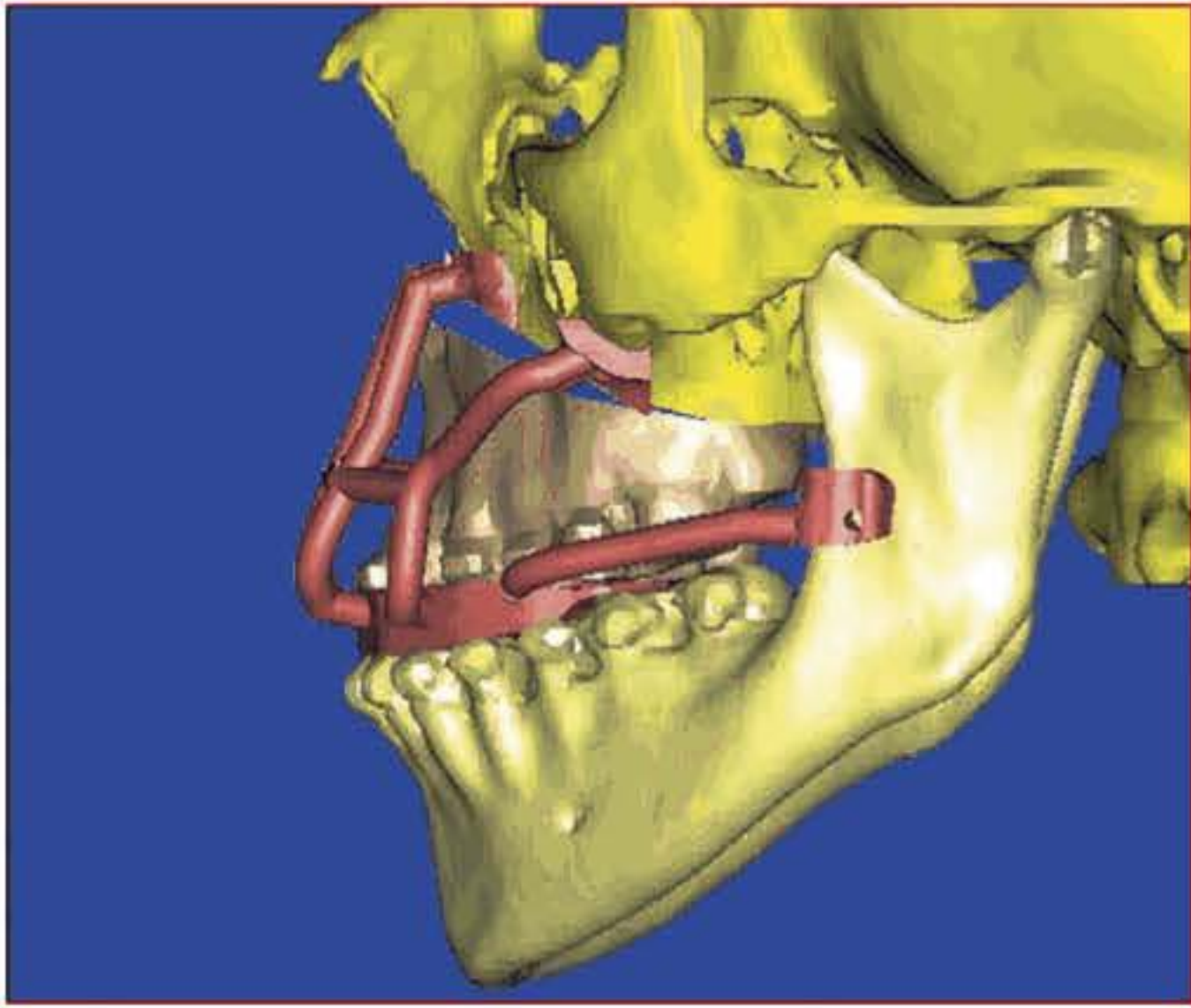


Fig 16-22 The 3D splint drafted on the computer. It facilitates the exact intraoperative transfer of the virtual surgical plan and the maintenance of the centric position of the condyle in the temporomandibular joint.



Fig 16-23 Stereolithographically produced 3D splint for intraoperative transfer of the virtual plan and for maintenance of the centric position of the condyle in the temporomandibular joint.

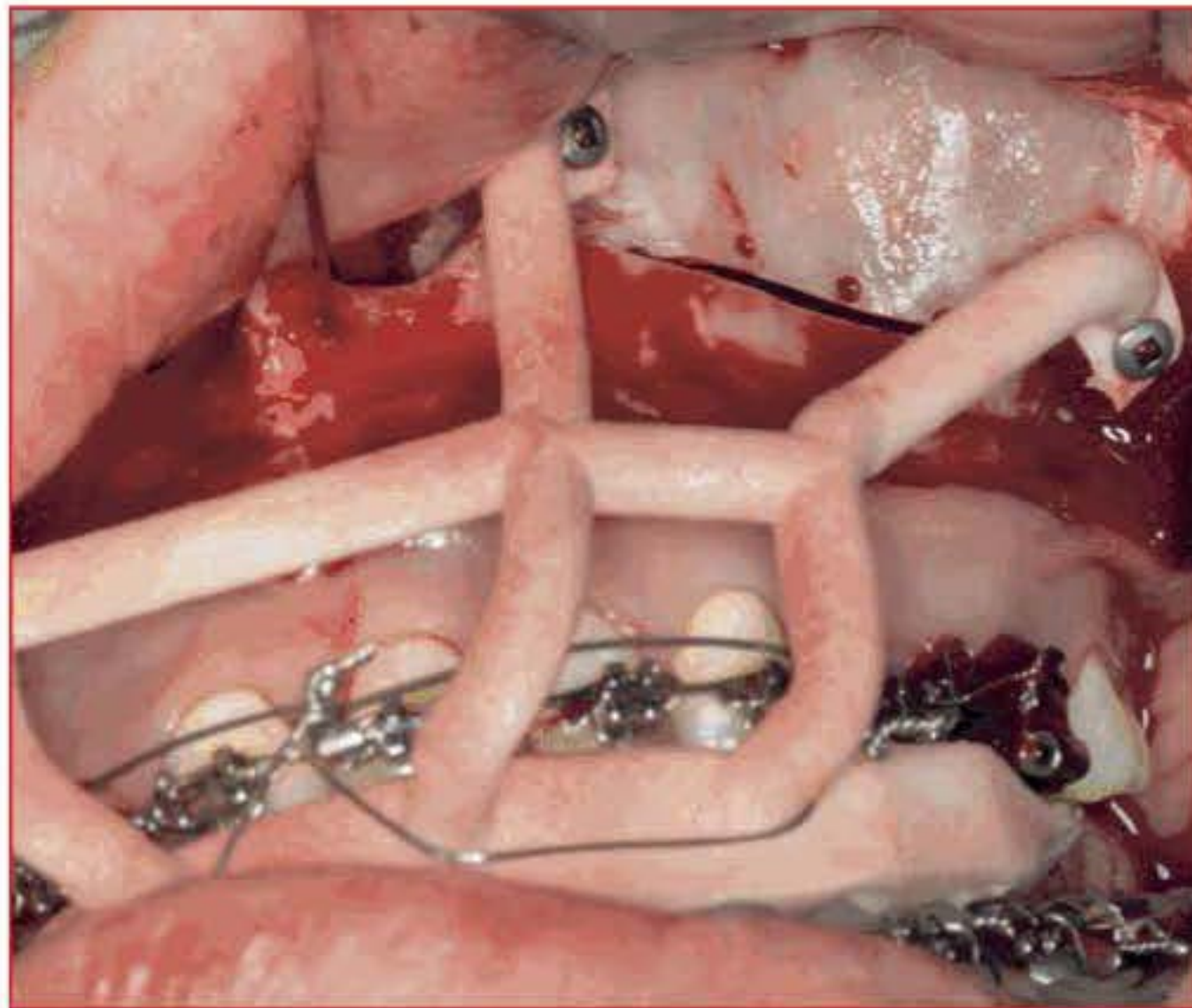


Fig 16-24 Intraoperative transposition of the maxilla using a newly developed 3D splint.

Implementation of the virtual plan

Another important feature of modern 3D planning modules is that the surgical splints can be designed directly on the virtual environment.

We have developed 3D surgical splints that facilitate direct intraoperative implementation of the surgical virtual planning (Figures 16-22 to 16-24).

The 3D splints are designed to guarantee the spatial position of the bone segments via the 3D support devices. Moreover, the centric position of the condyle in the temporomandibular joint is maintained. The splints can then be manufactured using stereolithographic technology, rapid prototyping or by 3D milling machines (Figure 16-23).

16.1.3 Summary

Modern 3D craniofacial planning software facilitates more exact diagnostics and evaluation. In addition, surgery can be planned virtually and the osteotomy lines can be defined. Another important advantage of computer-assisted planning modules is the option of producing 3D surgical splints directly and individually. We have developed 3D splints for the intraoperative implementation and transformation of the virtual surgical planning in order to improve the surgical outcome and to ensure maintenance of the centric position of the condyle in the temporomandibular joint.¹² The system also allows soft tissue to be simulated. Initially, the planning module was developed for CT data sets. However, the image quality of the CBCT data used here is just as suitable for 3D planning.

16.2 References

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Joachim E. Zöller
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Cone-beam Volumetric Imaging **in Dental, Oral and Maxillofacial Medicine**

Fundamentals, Diagnostics and Treatment Planning

With contributions by:

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Foreword

The diagnostic requirements in dental medicine are determined not only by oro-maxillofacial surgical therapeutic concepts but also by the increasing esthetic expectations of the patient. The trend to performing even extensive dental surgical procedures on an outpatient basis requires minimally invasive surgical techniques so that any necessity for postoperative inpatient treatment is largely avoided. Successfully performing minimally invasive surgical techniques requires a comprehensive three-dimensional diagnostic system, which also reduces the risk of complications. Therefore, we at the University of Cologne quickly initiated the use of three-dimensional imaging for computer-assisted surgery.

However, three-dimensional radiological imaging has not yet been routinely established in dental medicine and generally dentists have used the orthopantograph for diagnostic purposes. The development of cone-beam volumetric imaging was intended to allow the use of legally permitted levels of dental radiation for a wider range of applications. Using this technique a computed tomographic scan of the cranium is an acceptable item for billing under medical fees schedules in Germany. In addition to the use of the technique for clear dental indications, it was also important to assess how good it would be in detecting asymptomatic conditions. In the initial trial phase, we were surprised by the frequency of discovery of asymptomatic pathological entities by chance. This led to the idea of illustrating the various, sometimes rare, findings in an atlas to provide the user of cone-beam volumetric imaging with a reference for use in day-to-day assessments.

The GALILEOS software primarily used in this atlas is unique because it produces a three-dimensional orthopantograph that can be studied three-dimensionally using the assessment window. Naturally, this dynamic assessment cannot be illustrated in a book. Therefore, we have compiled a DVD with an original data set and numerous on-screen videos of assessments in different dental disciplines in order to demonstrate the identification of anatomical and pathological structures.

We hope that the first-time reader will find much enjoyment in this introduction and we hope to provide the experienced reader with a reference work for the various findings.

Prof. Dr. Dr. J. E. Zöller
Dr. J. Neugebauer
and co-authors

The dentist's working volume is hardly more than one liter, but this human body part contains within a very confined space a multitude of bones, vessels, nerves and anatomical structures of singular importance to the patient's quality of life and communication options.

Therefore, radiological diagnostics has represented an essential source of information for the dentist's spatial orientation since the beginnings of modern dental medicine. However, classical radiological techniques still depict this information in two dimensions. Three-dimensional radiological diagnostics enables the dentist to acquire accurate spatial information. However, regular utilization of this technology has been limited by the high equipment cost and the radiation exposure, which is not justifiable in all indications. Therefore, these systems have essentially developed under radiological considerations and do not meet the dentist's needs for pathological assessment.

The GALILEOS system that has been scientifically tried and proven at the University of Cologne is the first method that enables the dentist to perform three-dimensional diagnostics in dental radiology. All indications in which cone-beam volumetric imaging is indicated in the oro-maxillofacial area are excellently described in this atlas. The numerous, well-documented case examples provide the new user with an orientation, particularly with regard to the recognition of secondary findings, since the entire facial cranium is always documented in a single image.

However, in addition to diagnostics, the use of this three-dimensional information is equally important for the course of further treatment. The oral surgery, orthodontic and implantological therapy options are presented with numerous examples. The rare indications for computer-assisted navigation or orthognathic surgery also illustrate the options available in system applications.

In this work, the team of authors with Prof. Zöller discuss the scientific studies carried out in recent years and demonstrate the utilization of the technique, both scientifically and in practice, using numerous patient examples. Modification of three-dimensional image data for dental radiology thus adds a new therapeutic dimension for the dentist. To meet the increasing demands of our patients for minimally invasive procedures and optimal restoration of lost or damaged dental substance, three-dimensional diagnostics with familiar dental imaging is another important tool for high-quality dentistry.

Prof. Dr. Fouad Houry

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